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THE MAGNESIUM SPECTRUM UNDER REDUCED PRESSURE

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In a recent paper[1] certain modifications of the magnesium spectrum obtained by using alternating currents in a partial vacuum were described. It is now proposed to give a brief account of the phenomena observed with direct currents, which enabled the spectrum and appearance of each electrode to be studied separately. For this purpose the current from a 2000-volt transformer was rectified by means of a battery of 48 lead-aluminum cells arranged in four groups in order to make use of each half-period. In this way a unidirectional but pulsating discharge was obtained intermediate in properties between the spark and the arc.

The electrodes were always clean magnesium rods rather less than ¼ inch (6 mm) in diameter, inclosed in glass tubes except for ½ inch at the end. The distance between them was from ¼ to ½ inch, and the working pressure, unless otherwise stated, from 2 to 3 centimeters of mercury. The gases used were air, hydrogen, nitrogen, oxygen, and water vapor, and the primary object of the research was to investigate the mode of occurrence of the "hydride" spectrum.

Two distinct and well-defined types of cathode discharge can be recognized. In one the well-known cathode glow outside the Crookes dark space is the most marked feature. In the other type this glow is absent and in its place several isolated point discharges flicker about on the surface of the otherwise dark electrode. The two forms may

[1] *Proc. R. S.*, **80**, 218, 1908.

occur independently or together, but the second is the most persistent and the most readily obtained and there is often some difficulty in eliminating it when only the first is wanted.

The cathode glow, although so conspicuous in vacuum tubes, is by no means so prominent under the present conditions, and the only gas in which it is well developed is hydrogen. Again, in hydrogen there is a definite sequence of phenomena observed in no other gas. The cathode glow, which at first gives only a hydrogen spectrum, becomes gradually permeated by magnesium ions derived from the cathode until the hydrogen spectrum disappears (excepting a trace of the C and F lines), and only that of the metal remains. Then an unstable state is reached and the discharge suddenly brightens up with a copious emission of metallic fumes. In the former paper this was said to occur at the fusing point of the electrode. This is not necessarily the case; the electrode may fuse or it may waste away to a thin shred without losing its stiffness.

The first type of cathode discharge has two prominent characteristics: (1) Whenever it appears, and whatever the gas, the cathode gets hot; (2) the complicated band spectrum attributed to magnesium hydride is completely absent, in spite of the surrounding atmosphere of hydrogen. It gives an ideal sharp-line spectrum, and this simplicity of structure is not merely a special property of magnesium; calcium, which also has a band spectrum, exhibits the same peculiarity, and there is a strong probability that a general law is involved.

A portion of the cathode-glow spectrum in dry hydrogen is shown in Fig. 10, containing also sodium lines derived from the glass tubes.

The second type of cathode discharge (which will be termed for convenience the "jet" discharge) occurs in all gases, and several sub-varieties can be recognized by appearance and spectrum. Some of these depend on the emission of occluded gas, but this does not appear to be an essential factor. Two characteristic features are again apparent: (1) the coolness of the cathode; (2) the great intensity of the "hydride" bands in the spectrum of the jets, if only the merest trace of hydrogen or water vapor be present. These facts also hold good for calcium.

The sequence of changes mentioned above as taking place in the cathode glow in hydrogen cannot be obtained with certainty unless phosphoric anhydride is present in the discharge vessel, and even then the heating of the glass tubes covering the electrodes is exceedingly likely to drive off decomposition products which at once bring about the second or "jet" state. Hence success in obtaining the cathode-glow phenomena alone is a matter of some difficulty. The eruptive jets may be only feebly present, or they may entirely replace the glow, and they are certain to appear unless the gas is well dried.

In hydrogen the "hydride" spectrum was often found to be present at the anode, even when the cathode glow was without a trace of it, and as in other gases it also appeared at the anode when present in small quantity the conviction gradually arose that it was naturally an anode spectrum and that it never occurred at the cathode except in the spectrum of the jets. The presence of phosphoric anhydride always weakened it considerably, but in this gas never completely eliminated it when the rectified current was used. The anode itself is little attacked at first, but it becomes more conspicuous the longer the run and may itself supply ions, occasionally but very seldom fusing. In some experiments on the action of a magnetic field, the anode was frequently found to have received a deposit of metal in one place and to have been eaten away in another.

As no perceptible absorption of hydrogen occurred, it was evident that a solid hydride could only be present in traces, but a gaseous compound might possibly be formed without absorption. This was often looked for without success. The fumes deposited on the sides of the vessel were also examined. As a rule, but not always, they were spontaneously inflammable, taking fire in the globe when air was admitted or in a few seconds after removal. It soon became apparent that the metal dust was ignited by a variable quantity of some foreign substance and that the magnitude of the effect was related to the amount of action on the glass tubes covering the electrodes, chiefly at the cathode. Here the conductivity is reduced by the formation of a well-developed cathode glow, and the discharge then breaks its way through the glass, avoiding the metal end. There is much development of sodium flame and spectrum, and the current increases. It is partly the old "Hittorf effect." Various facts suggested that probably metallic sodium was formed in small quantity, and that this ignited the dust. Consequently it was somewhat difficult to collect fair quantities of the materials for analysis, and such estimations as were possible merely confirmed what was already known, i. e., that if any solid hydride existed it must be exceedingly small in amount. No satisfactory way of avoiding the use of glass tubes was found. Silica tubes were destroyed in a few seconds by intense chemical action; porcelain was also strongly attacked, in each case magnesium silicide being formed.

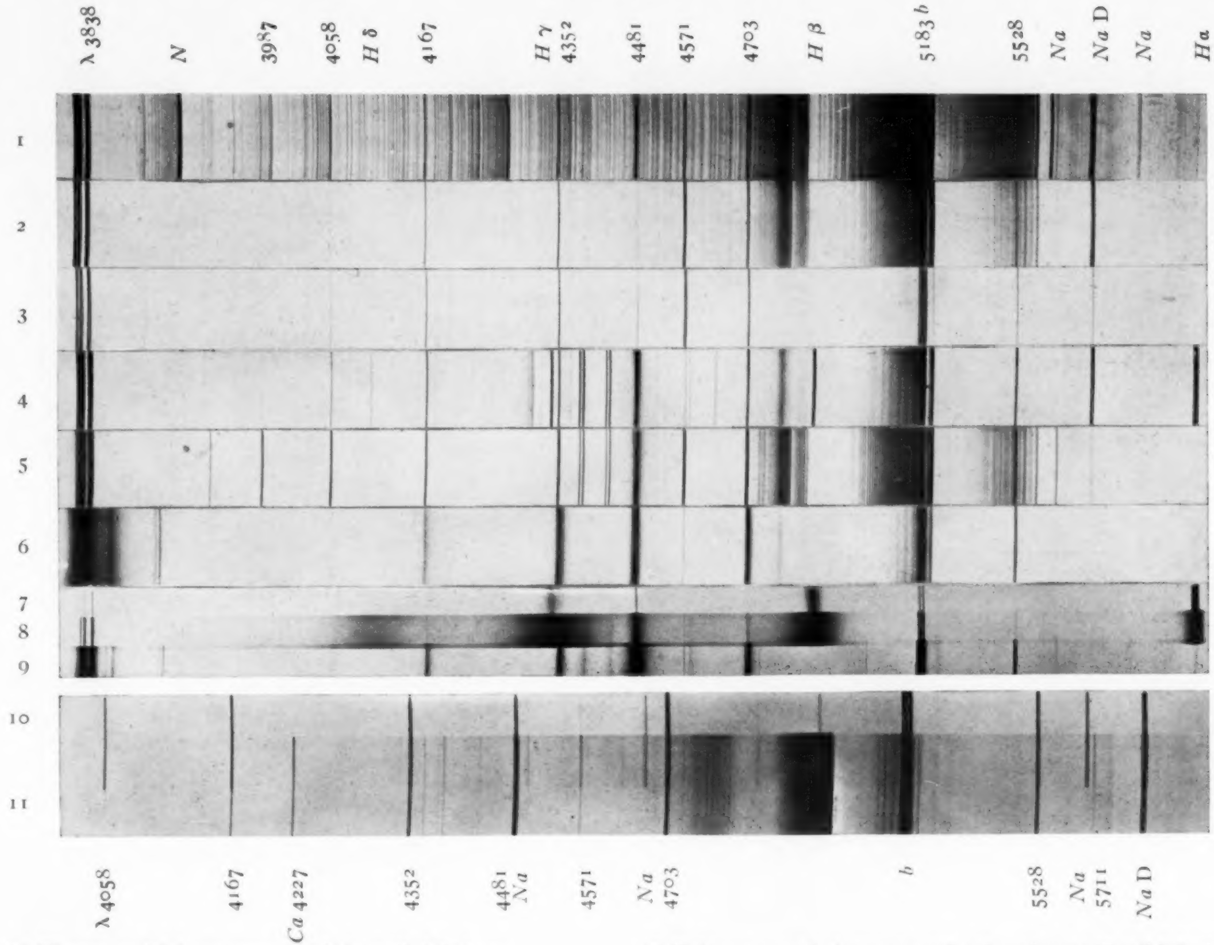
In order to obtain a metallic deposit free from chance impurity it was necessary to abandon the rectified current, and to resort to the ordinary low-tension arc discharge in a hydrogen vacuum, for in this case no inclosing tubes are required. Then the dust was never spontaneously inflammable, and when heated in a vacuum obtained by a mercury pump only such traces of hydrogen and oxides of carbon were obtained as might be expected from almost any materials heated in glass vessels. There was no suggestion of any gaseous compound.

The spectrum of the arc in vacuo has been so exhaustively studied by many observers that only a few observations were made for the sake of comparison. It was at once evident that the "hydride" spectrum was present in very great intensity, apparently occurring more persistently and readily than in any other form of discharge, and further, there was no perceptible difference between the spectra obtained at pressures of from ½ to 2 centimeters in air (dried or not dried), and in dry hydrogen. Attempts were made to get rid of the "hydride" spectrum in dry air, but without much success, and although it was certainly weakened and temporarily eliminated by repeated pumping, it always appeared again after a few minutes' run, the hydrogen lines C and F also becoming visible.

Hence the arc, in vacuo, is especially favorable to the development of the "hydride" spectrum, and the more intense the arc the stronger it becomes, but in consequence of the ready fusion of the electrodes the method offers certain practical difficulties, and it was not found possible to examine the anode and the cathode spectra separately.

The most striking fact about the arc spectrum as a whole is its marked resemblance to the "high-frequency" spectrum obtained under certain critical conditions with induction coil and Leyden jars. They are so nearly identical that it is not always easy to distinguish between them. The most noticeable difference is the absence

PLATE XIV



(1) Nitrogen, not dried, 3cm pressure, cathode, rectified discharge.
(2) Air, not dried, 2cm pressure, anode, rectified discharge.
(3) Nitrogen, dry, 3cm pressure, anode, rectified discharge.
(4) Hydrogen, dry, ½cm pressure, coil and condenser ("Flame" state).
(5) Air, dry, ½cm pressure, arc.
(6) Hydrogen, atmospheric pressure, arc.
(7) Hydrogen, atmospheric pressure, coil and condenser with self-induction.
(8) Hydrogen, atmospheric pressure, coil and condenser without self-induction.
(9) Air, atmospheric pressure, coil and condenser with self-induction.
(10) Hydrogen, dry, 3cm pressure, cathode glow, rectified discharge.
(11) Oxygen, dry, 3cm pressure, anode, rectified discharge.

or weakness of the chief hydrogen lines in the arc spectrum and their sharpness and strength in the coil spectrum. Also the line λ 4481 is more diffuse in the arc and sometimes reversed.

It may be remarked that Liveing and Dewar found the Leyden jar spark unfavorable to development of the hydride spectrum under the conditions of their experiments. I have found that it is completely absent, even as a trace, from the spectrum of the jar spark, in vacuo, unless the discharge assumes the specialized form termed in the former paper "the high-frequency flame" discharge; then it is invariably present in hydrogen and in most other gases. Also, in hydrogen it cannot be eliminated by any process of drying, although that method is effective in other gases.

This spectrum is shown in Fig. 4, Plate XIV. It depends on a very characteristic type of discharge, only obtained when a strong oscillatory current is used with electrodes of very small mass. Fig. 5 is the arc spectrum in dry air, at ½ cm pressure, but it will serve almost equally well to represent that spectrum in air or hydrogen whether dried or not. The only difference is that in air the fluting at λ 5007 is visible at first, rapidly becoming weaker and disappearing as the hydride spectrum increases in strength, while the line λ 4571 is of somewhat variable intensity. In Fig. 4 the carbon fluting at λ 4315 appears as impurity; in the arc spectra the red carbon line at λ 6579 is often seen.

The one common factor connected with the origin of the two spectra shown in Figs. 4 and 5 is high current-density. Whenever this is sufficiently great the hydride spectrum is strong, and most difficult to eliminate by attempting to get rid of hydrogen or water vapor. The intensity of the two pairs of well-marked lines between λ 4481 and λ 4352 (observed originally by Porter and afterward examined by Fowler and Payn)[1] is entirely dependent upon the same factor, but they are not in any way related to the hydride spectrum. They are simply very "short" metallic lines, and are often well seen in the types of spectra shown in Figs. 1, 2, and 3, although seldom strong enough to appear on the negatives. They have not been seen in the cathode-glow spectrum, but are a well-marked feature in the eruptive jets, a fact which seems to indicate that this latter form of

[1] *Proc. R. S.*, **72**, 257, 1903.

cathode discharge is also associated with locally great current-density.

As Crew did not mention the appearance of the hydride spectrum in his work on the hydrogen arc at ordinary pressures, a photograph was taken under these conditions. The result was the spectrum shown in Fig. 6, in which the hydride is distinct enough, but still quite weak. The metallic lines are all broad and diffuse except λ 4571, which is fine and sharp, and a remarkable feature is the very great relative intensity of the violet *Mg* triplet and the fainter lines close to it, two components of the triplet being reversed. Morse[1] has noticed a similar marked intensity of this triplet in the Wehnelt break spectrum of *Mg* wire in *HCl*, and Wilsing[2] also refers to very diffuse absorption lines in this position obtained by spark discharges in water.

The well-known jar-spark spectra obtained in hydrogen and air at atmospheric pressure are appended in Figs. 7, 8, and 9, for purposes of comparison. The spark in hydrogen is quiet and not very luminous, forming a great contrast to the noisy bright spark in air. The metallic lines are feeble and the gaseous lines strong and diffuse, while the hydride spectrum is reduced to a faint trace of its strongest edge at λ 5211, and is best seen with self-induction in the circuit. It will be noticed that the arc spectrum in hydrogen and the spark spectrum in air, both at ordinary pressure, bear a marked resemblance to each other.

The mode of occurrence of the hydride spectrum in gases other than hydrogen was carefully examined, using the rectified current. In all gases a conspicuous effect is the initial heating of the cathode. This is especially noticeable with a clean electrode and rapidly diminishes if the metal becomes oxidized and hence a cathode may almost instantly lose its shape with a small current and then carry a much larger one for an indefinite period without further fusion. It is partly an instance of the Wehnelt effect.

In an air vacuum the cathode glow is absent, the initial heating is soon over, and long runs may be obtained with less danger of fusion than in hydrogen. At first the spectrum is almost entirely gaseous, chiefly nitrogen flutings and the oxide fluting at 5007. As the dis-

[1] *Astrophysical Journal*, **19**, 169, 1904.

[2] *Ibid.*, **10**, 121, 1899.

charge, somewhat irregular at first, settles down into the eruptive jet form, this spectrum disappears and unless the gas is specially dried the hydride spectrum develops as the 5007 fluting gets weaker, and it may be observed steadily with great intensity for a long time. These statements also apply to nitrogen not completely free from oxygen.

All the best photographs of the hydride spectrum were obtained in this way. No really good negatives of the fainter detail were obtained in hydrogen, chiefly because the use of that gas gives no tangible increase in brilliancy, and greatly adds to the difficulty of obtaining a long run.

The cathode spectrum in air largely deprived of oxygen is shown in Fig. 1, the chief hydride bands being much overexposed in order to bring out the fainter portions. It will be seen that it extends across the whole range of the visible spectrum. Traces of nitrogen flutings are also present. When the discharge vessel contains phosphoric anhydride the hydride spectrum either completely disappears or is reduced to the merest suspicion of its strongest edge.

Meanwhile a gradual change has been taking place in the appearance and spectrum of the anode. This does not begin until the oxygen is used up, as evidenced by the disappearance of the 5007 fluting, and requires a fairly long run and a strong current to bring out properly. The anode at first is not very conspicuous, except for the nitrogen glow. In the end it becomes covered with numerous minute specks of light shining steadily on a bluish ground tint. The gaseous lines disappear, the hydride bands are present but relatively weak, and there remains a sharp metallic spectrum in which the line 4481 is always weak and sometimes absent, while the line 4571, which has been steadily increasing in strength, becomes the brightest line present (excepting the *b* triplet). Exactly the same result is obtained when the air is dried, except that the hydride spectrum is absent, and it is still more readily obtained when the air is first largely deprived of its oxygen.

Figure 2 shows this anode spectrum in air after a long run. It was obtained immediately after one similar to Fig. 1, by merely reversing the direction of the current, and in fact this spectrum was visible at the anode while Fig. 1 was being photographed. Fig. 3

is the anode spectrum in fairly dry and pure nitrogen, and shows the influence of phosphoric anhydride in eliminating the hydride spectrum. It shows traces of cyanogen, which is a common impurity.

Many attempts were made to observe the discharge in pure dry nitrogen, but it was extremely difficult to insure that no oxygen was present. The greater its purity, the greater is the initial heating of the cathode, which almost inevitably fuses, and the more erratic is the discharge at its commencement. The characteristic anode glow and spectrum appear after a time as usual, and when a trace of the hydride is present it is strongest at the anode. Nitride is formed at both electrodes, but never in large quantity, and the absorption of gas goes on very slowly. It does, however, seem probable that the enhancement of the line 4571 is in some way related to the formation of nitride. Professor Hartley[1] photographed the spectrum of magnesium under reduced pressure, using a spark discharge with condenser, and from his observations suggested that it was more than probable that two pairs of lines, one at 3830 and 3837, and the other about 5200 and 5209, were the spectrum of magnesium nitride. The first two are components of, or near to, the violet triplet and these I do not find affected in any way by the presence of nitrogen. The only lines in the second region (apart from the complex shading of the hydride spectrum) are (1) the principal hydride edge at 5211, (2) two oxide lines at 5205 and 5191. Under the conditions of his experiments the hydride edge might easily be present. None of my negatives suggests the existence of any new lines or flutings, and provisionally I regard the spectrum shown in Fig. 3 as characteristic of nitride formation within the region covered by the photograph.

When the rectified discharge is taken in water vapor at low pressures, there is as usual a short initial stage with hot cathode. At first the water vapor or hydrogen spectrum is very strong, but this gradually disappears as time goes on. A small current does not bring out the hydride spectrum; at about 0.5 ampere it appears faintly and at about 1 ampere the anode suddenly swells up and glows red hot throughout, becoming a mass of oxide without fusion and liberating hydrogen in quantity. At the same instant the hydride spectrum flashes out in great intensity, but of course it is only visible

[1] *Proc. R. Dublin Soc.*, **11**, 245, 1907.

for a few seconds in consequence of the great rise of pressure. The cathode is but little attacked. The anode can be brought up to the point of ignition slowly or rapidly by regulating the current, the hydride spectrum is always weak except during the reaction, and, as in all cases, the C and F lines of hydrogen tend to weaken and disappear as that spectrum becomes stronger.

It may be remarked that the hydride spectrum is also seen when magnesium is burnt in a current of steam at ordinary pressures—the combustion lasts only a few seconds and there is a strong continuous spectrum, but the brightest hydride fluting is always visible.

When the rectified discharge is taken in pure dried oxygen at a pressure of 3 cm not a trace of the hydride spectrum is seen.

There is some initial heating of the cathode, but it quickly subsides and there is no difficulty on that account. There is no cathode glow and although the cathode discharge is of the eruptive jet type, it exhibits certain peculiarities. There is little absorption of gas with small current, but if it be unduly increased, absorption becomes increasingly rapid, and one of the electrodes, usually the anode, may suddenly ignite and burn to a mass of oxide.

The spectra obtained are highly characteristic. At the anode there is a sharp metallic spectrum, in which the two pairs of lines between 4481 and 4352 are often well seen. The line 4481 is strong and sharp, while 4571 is weak. A noticeable feature is the presence of the calcium lines 4227, 3968, and 3933, which no doubt are derived from the glass, but seldom observed except in oxygen. As might be expected the oxide spectrum is very pronounced, and as there is comparatively little continuous spectrum this method affords a convenient means of examining it. Good negatives are somewhat difficult to obtain; if the current is too weak the fainter detail is not brought out properly, and if only a little stronger, one of the electrodes is liable to burn up. Again, as the electrodes become oxidized the continuous spectrum due to incandescent points of oxide becomes increasingly troublesome.

At the cathode the oxide bands are also seen, but here the prominent feature is the presence of the line spectrum of oxygen in considerable intensity.

A portion of the anode spectrum is shown in Fig. 11. After this exposure on one-half of the slit the apparatus was well washed out with hydrogen, again exhausted, and the same electrode was then used as cathode. In this case the cathode glow appeared free from the jet discharge and Fig. 10 was obtained. At the same time the hydride spectrum was visible at the anode.

The anode spectrum in oxygen exhibits several points of interest. At the red end I find a series of bands with edges sharp toward the red which do not appear to have been previously mentioned. These would be easily photographed were it not that they are first to become lost in the continuous spectrum which gradually increases in intensity as the oxidization of the electrodes proceeds, and hence only short exposures are possible. Visual observations present similar difficulties. Approximately their positions are 6589?, 6314, 6063, 5781, 5477, 5284, 5249, and there are several more edges too faint for measurement. The first of these values is a very rough estimate, the others are probably correct within one or two units. In the neighborhood of the *b* triplet there is a fluting with maxima at 5205, 5191, 5162, 5145, 5123, 5110, for which my measurements agree almost exactly with Eder's, but his line at 5210.7 is almost certainly the principal hydride edge.

Another conspicuous feature is a fluting without sharp edges between the 5007 fluting and the weak *Mg* line at 4730, in the same place as one of the stronger hydride flutings, also without sharp edges. This again does not appear to have been previously mentioned. It cannot be resolved visually, owing to its extreme faintness and it was not photographed until observations were made in oxygen. In the *Denkschriften* of the Vienna Academy (**74,** 54, 1903), there is a plate accompanying a paper by Eder which shows one or two lines faintly resolved, but buried in a strong continuous spectrum which begins just at this point and extends far into the violet.

The wave-lengths of the principal edges are approximately 4826, 4820, 4811, 4802, 4791, 4781, and 4771.[1] The edge at 4781 is rather diffuse, and several faint lines lie between it and 4791. Several other lines, somewhat irregularly spaced, have been measured between 4771 and 4730, which may also belong to the system.

The remaining portions of the oxide spectrum have been frequently

[1] A first notice of this fluting appeared in *Nature*, July 2, 1908, p. 198.

observed, and although very strong in these photographs, do not call for special remark. Eder has catalogued a series of bands from 3091 to 3865 which certainly extend as far as 4100, and in fact the whole space up to the *b* triplet appears to be full of exceedingly faint detail. My negatives also show a sharp, well-marked line at 4368, and a fainter one at 4381 whose origin has not been satisfactorily determined.

Returning to the consideration of the hydride spectrum, from the whole series of observations the following conclusions can be drawn: (1) This spectrum represents some transitional and unstable state; (2) its production depends far more upon the nature of the discharge than upon the quantity of hydrogen present, although the presence of this gas in some form appears to be necessary; (3) a trace of water vapor is even more effective than hydrogen, but its presence cannot be regarded as an essential condition ; (4) if really due to a hydride, that body is probably decomposed as fast as it is formed.

It is very suggestive that no increase in the extent and brightness of this spectrum is noticed when a hydrogen atmosphere is used, instead of one in which hydrogen is only due to occluded gas or water vapor and that in the latter case the gas never gets used up, with the disappearance of the corresponding spectrum, as a trace of oxygen does. It is also suggestive that the most important factor appears to be current density at the electrode. Whenever this becomes great enough, the hydride spectrum appears, in spite of efforts to eliminate hydrogen, whereas when it is small, as in ordinary spark discharges, that spectrum is either faint or altogether absent, even in an atmosphere of hydrogen.

The necessity for hydrogen is the only evidence that this spectrum is due to the formation of a compound. The point can scarcely be said to be definitely settled experimentally on account of the practical impossibility of eliminating that gas, but on the whole the facts seem decidedly in its favor. It does not, however, seem necessary to assume the existence of an actual hydride, except for convenience, and unless the term "compound" is to have a very extended meaning. It is perhaps worth remarking that what is generally termed the spectrum of a compound is really that of certain processes which take place during its formation or decomposition, the true nature of the vibrating system being unknown. For instance, MgO, once formed, merely gives a continuous spectrum.

Again, the undoubted formation of nitride appears to show itself only by the strengthening of a single line.

Professor Hartley, as the result of his extensive and long-continued researches on the band spectra of metals in the oxy-hydrogen flame, has recently stated that these are due to the atoms and not to compounds, and his far-reaching conclusions appear to cover the case of magnesium hydride.

The existence of two kinds of cathode discharge, one free from the hydride spectrum, and the other highly favorable to its appearance, seems to be a fact of some importance. In this region the phenomena of discharge depend largely upon the behavior of these positively charged bodies which constitute the canal rays, and it is not impossible that here we may have to reckon with the two kinds of positive entities common to all gases, whose existence has been established by Sir J. J. Thomson. Again, it seems highly probable, as an inference from much experimental data not dealt with in this paper, that the eruptive jet form becomes greatly developed in, and is typical of, the ordinary arc discharge, being dependent on current-density, while the cathode-glow form becomes more prominent in the spark and in vacuum tubes. But in neither case does the preponderance of one type necessarily mean the total exclusion of the other.

Much work as yet incomplete has been done to throw light on the state of affairs at the electrodes. As regards the cathode, whatever the state of Mg particles may be when driven off into the cathode glow in hydrogen, they appear almost immediately to act as if either positively charged or neutral, and in spite of their intimate mixture at first with hydrogen ions in that glow, no trace of the hydride spectrum is seen. On the hypothesis of a compound, this may be explained by supposing the Mg and H ions to be similarly charged and unable to combine, and the fact that the hydride spectrum can in some instances be seen simultaneously at the anode may be regarded as indicating that it is due to a negatively charged aggregate. There are certainly two well-marked stages in the evolution of fumes from the cathode. At first they consist of extremely finely divided metallic dust, which readily rubs up to a bright mirror, but after a long run with rather heavy current there is a somewhat sudden change; much larger metallic particles are projected, and also a number of small metallic spheres, very perfectly formed and with a brilliant metallic luster, which are hollow. They are thin-shelled bubbles averaging about a millimeter in diameter and are interesting as being produced at a surface which as a whole does not necessarily soften. Similar bubbles may be seen in arc residues, but they are much larger and more numerous with the rectified current.

A preliminary study of other metals used as electrodes has brought out certain important differences of behavior; for instance, calcium seems to waste away most rapidly at the anode. It is hoped to deal with these matters more fully in a later paper.

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THE RELATIVE INTENSITIES OF THE YELLOW, ORANGE, AND RED LINES OF CALCIUM IN ELECTRIC FURNACE SPECTRA[1]

By ARTHUR S. KING

The large electric furnace in the Pasadena laboratory[2] has recently been used by the writer to study the effects of different temperatures on the calcium spectrum in the region of greater wave-length, specia attention being paid to some twenty lines occurring from λ 5857 to λ 6718, which were affected very differently by changes in the furnace temperatures. All of the prominent arc lines in this region are given by the furnace, and the experiments were arranged to bring out not only the effects of varying the temperature, but also of increasing the quantity of vapor, to observe whether any lines in this region show a behavior similar to that of the "flame line" λ 4227, which was shown in a former investigation[3] to respond but slightly to change of temperature, while enormous widening was brought about by a large increase in the amount of calcium vapor present.

The photographs were made with the vertical Littrow spectrograph with an objective of 13 feet (4 m) focal length, the first order of a 5-inch (13 cm) plane grating being used. The plates were Seed's "27," sensitized by the Wallace three-dye process.[4] The furnace was charged with a few pieces of clean metallic calcium, a large or small amount being used according to the vapor-density desired. The tube was heated in vacuum, first with an e.m.f. of 20 volts which rapidly raised the temperature, reaching in about five minutes a temperature of approximately 2800° C. as measured by a Wanner pyrometer. An exposure was made as the temperature rose, then others of one-half to one minute at the maximum temperature. A vigorous vaporization of the carbon was then taking place. The current was broken

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 35.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 32; *Astrophysical Journal*, **28**, 389, 1908.

[4] *Astrophysical Journal*, **26**, 299, 1907.

and 15 volts substituted, after which one or two low-temperature exposures were made, fifteen to twenty times the length of the exposure now being required to produce a photograph of the same average strength as that at the highest temperature. No close value for this temperature can be given, as it was somewhat variable, the heating of the jacketing running up the temperature so that is was necessary frequently to break the current for a few seconds. The average temperature seemed to be about 2200° C., probably never rising above 2400° C.

The influence of vapor-density was tested by using very different amounts of calcium in the furnace tube. These were given (1) by the empty tube, the graphite of which contains enough calcium to show the stronger lines distinctly; (2) a small amount (about 0.1 gm) of metallic calcium; (3) a large amount (2 to 3 gms) of the metal.

It may be noted here that chemical action was present in these experiments to a greater degree than is the case when a substance not readily oxidizable is used in the furnace. The bright surfaces of the calcium became dulled while it was being placed in the furnace tube and further time was required to close the chamber and pump out the air. The result was that brilliant red bands appeared during the first minute of the heating. These soon died out for the most part, but some of them persisted through several exposures, especially when a large quantity of calcium was used. These weakened rapidly with time, and the strength of the calcium lines appeared to be quite independent of the existence of the bands, the lines being produced with equal facility whether the bands were strong or barely visible.

The following table includes the lines from λ 5582 to λ 6718, with their intensities in the furnace spectra at high and low temperatures for the three conditions of vapor density given respectively by a large amount of metallic calcium, a small amount, and by the empty tube. The estimates of intensity were made by comparison with a photographic scale in the manner described in a previous paper,[1] modifying the estimates when necessary according to the character of the lines. The spectra given by high vapor-density afforded the most complete material for comparison, on account of the average density of the two photographs being very nearly the same; but some allowance was

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

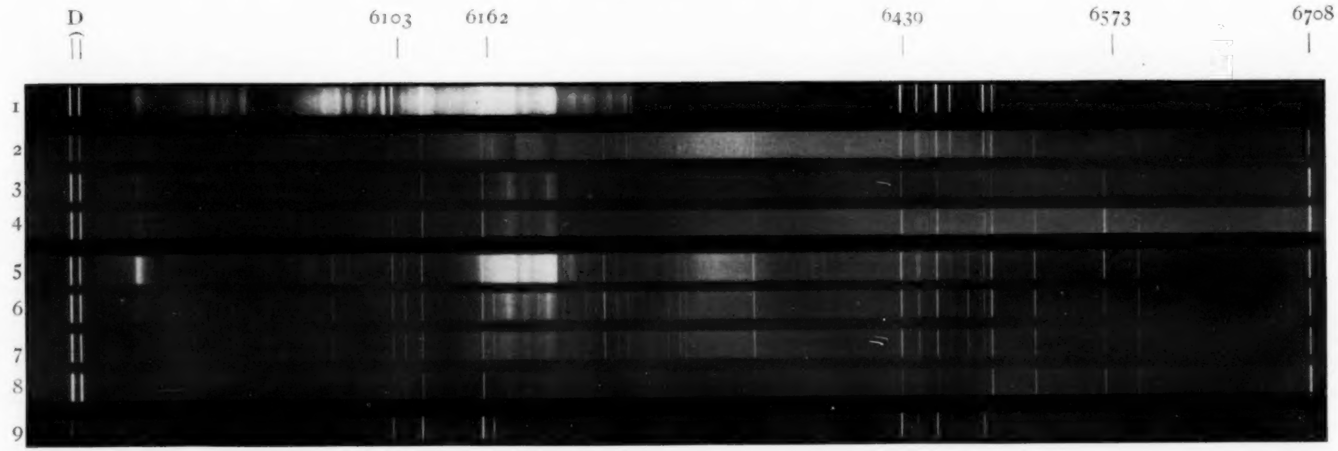
necessary for the lines at the higher temperature being widened and diffuse when much vapor was present, instead of sharp and black. In the spectra with less calcium present, the spectrum for the lower temperature was as a whole weaker than for the higher temperature, so that a factor of 2 is needed to bring the low-temperature spectra (in the fifth and seventh columns) to an average intensity comparable with that at the higher vapor-density. The intensities are given in the table without reduction.

	High Vapor-Density		Medium Vapor-Density		Low Vapor-Density	
λ	High Temp.	Low Temp.	High Temp.	Low Temp.	High Temp.	Low Temp.
5582.20	2	1	2	trace	*	1
5588.98	4	3	4	2	4	3
5590.34	2	trace	1	..	*	trace
5594.69	3	2	3	1	3	2
5598.71	3	2	3	1	*	2
5601.50	2	1	1	..	*	1
5603.08	2	1	1	..	*	1
5857.67	5	2	3	trace	5	1
5867.78	2	1	2	1	1	..
6102.94	9	8	9	6	9	6
6122.43	10	18	12	15	16	10
6161.50	1	..	trace	..	..	..
6162.39	8	24	14	22	20	15
6163.97	2	1	1	..	1	..
6166.65	3	1	2	trace	2	..
6169.25	4	2	3	trace	4	2
6169.78	6	3	7	1	6	3
6439.29	16	18	18	9	20	10
6450.03	10	6	8	2	6	3
6455.82	4	..	3	..	2	..
6462.78	14	15	16	7	15	7
6471.88	8	4	5	1	4	2
6494.00	12	9	10	3	10	4
6499.88	7	2	3	trace	2	1
6573.03	5	18	5	10	8	11
6708.18	20	80	24	60	30	70
6717.94	3	2	1	..	2	..

* Concealed by strong carbon fluting in this photograph.

Description of plate.—Plate XV reproduces the region from λ 5890 to λ 6708 for different temperatures and different quantities of vapor Photograph No. 1 gives the spectrum from calcium in the carbon arc a large quantity of the metal being present. Nos. 2, 3, and 4 are furnace spectra with much calcium in the tube, 20 volts being used on the tube for No. 2 with an exposure of one-half minute when the tube was very hot. Nos. 3 and 4 were taken with 15 volts on the tube and exposures

PLATE XV



The Spectrum of Calcium in the Electric Furnace, with Comparison Arc Spectra

Scale: 1mm = 5 Ångström units

of 5 and 10 minutes respectively after No. 2 had been made, the current being broken several times during No. 4 to keep the temperature down. No. 4 is most comparable in average intensity with No. 2, though No. 3 is useful to show the relative strength of some of the stronger lines at the lower temperature. Nos. 5, 6, 7, and 8 are furnace spectra with a small quantity of calcium in the tube. Nos. 5, 6, and 7 were taken with 20 volts on the tube and successive exposures of four, three-quarters, and one-half minute respectively as the temperature rose, there being no break of the current between exposures. No. 7 best represents the condition for high and nearly constant temperature, while Nos. 5 and 6 are of interest as showing the weakening of the bands as the vaporization progressed in the vacuum, it being possible to keep the lines of nearly the same intensity in the three photographs, by proper timing of exposures. No. 8 is a low-temperature spectrum taken with 15 volts on the tube and an exposure of seven minutes immediately after No. 7. A final arc photograph (No. 9) is added below for comparison, the amount of calcium and exposure time being so adjusted as to give the prominent lines with very weak bands.

Discussion.—Referring to the table, it is obvious at once that the calcium lines in this region differ greatly in their response to the stimulus accompanying increased temperature. The low-temperature lines may be at once selected from the first two columns of the table or by comparing any pair of photographs at high and low temperatures reproduced in Plate XV. These lines strengthen but slowly with rising temperature, while a number of lines barely visible at the lower temperature rapidly attain considerable strength with higher heating of the tube. Several sets of lines may be selected which show this effect in a striking manner, for example, λ 6122 and λ 6162 as compared with λ 6103; λ 6439 and λ 6463 as compared with λ 6450 and λ 6456; λ 6573 and λ 6708 as compared with λ 6718, and a number of other notable contrasts. λ 6103 must, however, be classed among the low-temperature lines.

The object of using different quantities of calcium in the furnace tube was to see how large a part vapor-density may be expected to take in determining the relative intensity of the spectrum lines, calcium being in many ways a favorable substance for a test of this kind. Comparing the first and third columns of the table, these spectra being taken at approximately the same temperature and with very different quantities of vapor, a few of the weaker lines show slightly stronger with higher vapor density, the most decided being λ 6471.88 and λ 6499.88. An interesting difference is seen between λ 6122 and λ 6162, their intensities being in the ratio 10 to 8 at the higher vapor density and 12 to 14 at the lower. It holds in all of the spectra, however, that λ 6122 strengthens with rising temperature more rapidly than λ 6162, so that if the tube were slightly hotter for the spectrum given in the first column the difference between the two lines should be in the direction observed. The same cause would account for the behavior of λ 6471.88 and λ 6499.88, both of these being high-temperature lines and rapidly strengthened as the temperature rises.

The line which we should expect to be most affected by vapor-density is the strong red line λ 6708, which is comparable in many ways to the "flame line" λ 4227, appearing strong at low temperatures with a mere trace of calcium present. It does not readily reverse, however (the widened appearance is due in part to poor focus at the end of the plate), and shows no decided change in appearance or intensity when the quantities of vapor are greatly different. An examination of plates taken in this and the former investigation, covering the spectrum as far as λ 3700, shows no lines except λ 4227 in which change of vapor-density has a decided effect. The conclusion to be drawn from the calcium spectrum is that while increase of vapor-density makes all of the lines wider and more diffuse, it does not appear promising as a general cause in producing changes of relative intensity among lines when temperature and other conditions remain unchanged; and these latter can be held constant for different vapor-densities much more nearly in the furnace than is possible in the arc. It appears probable that λ 4227 and some of the most decided "flame lines" in other spectra are in a class by themselves as regards dependence on vapor-density. However, a study under higher dispersion of the widening produced by increased vapor-density will be necessary for a full discussion of this point.

The *band spectrum* in this region is of interest for the present paper chiefly as an indication of the degree to which chemical action is present. The bands which appear in the furnace photographs occur, with one exception, also when metallic calcium is vaporized in the carbon arc burning in air and are presumably due to the oxide unless possibly they are given by the metal itself. As has been noted, the calcium became oxidized to some degree before the air could be removed from the furnace chamber. Photographs Nos. 5 to 8 of Plate III show the weakening of the band spectrum as the experiment progressed and indicate that this initial state of oxidation gave rise to the the bands. The increase of temperature during exposures 5, 6, and 7 might act to weaken the bands, but in that case No. 8, taken at a a lower temperature comparable to the beginning of No. 5 when the bands were most brilliant, should restore their intensity to some degree, which is not the case. The same argument makes it doubtful as to whether they can belong to the metal; since in that case they should show a behavior similar to that of the low-temperature lines (λ 6708, for example) instead of a steady fading away as time went on.

When a larger amount of calcium was used, the bands were much more persistent, as would be expected from the increased opportunity for chemical action. In No. 2 the stronger bands are seen reversed, while they are bright and fairly distinct in Nos. 3 and 4.

The band referred to, which does not appear in the spectrum of the arc burning in air, is that with prominent heads at λ 6389.3 and λ 6382.2, shaded toward the violet. They show distinctly in Nos. 2 and 5, especially in the latter, and are faintly visible on the negative in the low-temperature photographs. This is the band measured by Olmsted[1] and found especially strong in the calcium arc burning in hydrogen. The band is not usually perceptible in the calcium arc in air or when a plentiful supply of oxygen is present. Hydrogen or water vapor supplied to the arc with partial exclusion of oxygen bring it out strongly. In the furnace spectra it is favored, like the other bands, by the initial conditions when the furnace is heated up. It weakens with time and is not restored by lower temperature, so that it seems unlikely that this band belongs to the metal; while its behavior in the arc, as has been noted, is different from that of the other furnace bands. If the band at λ 6382–6389 is due to a hydrogen compound, this would most probably arise from moisture inside the steel chamber, which would be vaporized at the

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 21; *Astrophysical Journal*, **27**, 66, 1908.

first heating, and would then be rapidly pumped out, as the pump is usually kept working during the operation of the furnace. It is hoped soon to make further tests as to the origin of the band.

Comparison with sun-spot lines.—The sensitiveness of the calcium lines to temperature changes makes them favorable for use in testing the hypothesis that temperature is one of the chief agencies in causing the differences between the solar spectrum and that of sun-spots. The relation holds, quite as generally as in any spectrum examined, that all of the low-temperature lines are much strengthened in sun-spots, usually in the ratio of about 2 to 1 in photographs where the continuous ground is of the same density for both spot and solar spectra; while the two most conspicuous low-temperature lines, λ 6573 and λ 6708, are intensified in sun-spots in the ratio 15 to 1 and 5 to 0000 (on the Rowland scale) respectively. However, some condition exists on the sun which causes all of the calcium lines to be more or less strengthened in the spot and it frequently happens that some of the high-temperature lines, as for example $\lambda\lambda$ 5858, 6167, 6456, 6500, are considerably stronger in the spot than in the sun. There is a vital difference, however, between the character of these lines and that of the pronounced low-temperature lines, such as $\lambda\lambda$ 6103, 6122, 6162, 6439, in that the latter are very much widened and "winged" in the spot, the formation of wings being very slight for the group of high-temperature lines.

So much remains to be settled in regard to the causes of widening in solar lines, the matter being still further complicated by the existence of a magnetic field in sun-spots, which would cause lines to be widened differently according to the type of magnetic separation, that for the purposes of the present paper the matter may best be left with the statement just given of the general relation between the low- and high-temperature lines. An intensive study will soon be made of a few of the calcium lines under higher dispersion, to determine by a comparison of various laboratory conditions what causes are chiefly instrumental in the observed widening of these lines in solar spectra.

It may be well to state what is meant by the constant use in my electric furnace papers of expressions concerning the dependence of spectra upon "temperature," that necessary brevity of statement in the use of this word may not be mistaken for looseness. Nothing in the electric furnace experiments can claim to throw any light on the ultimate mechanism of radiation. We are, however, dealing here with temperature as the primary or rather the *initial* exciting cause; though the experiments leave open the possibility that other agencies, *results* of the high temperature, supply the stimulus finally needed to produce light. With the low voltage employed on the furnace tube, it is scarcely conceivable that the electric current produces any condition that would not be present if the tube were heated by a flame applied to the outside or were imbedded in a mass of hot material, the ease of producing a high temperature being the sole point in favor of the use of the electric current. All of the consequences of the electron theory may hold for the radiation in the furnace, provided we admit that the temperature supplies the necessary energy and controls its amount. This position of temperature as the primary excitation is the essential point of contrast between the furnace on the one hand and the arc and the flame on the other. In the two latter sources, high temperature is the *result*, in the one case of the electrical action, in the other case of the chemical processes of combustion.

Mount Wilson Solar Observatory
January 1909

THE 60-INCH REFLECTOR OF THE MOUNT WILSON SOLAR OBSERVATORY[1]

By G. W. RITCHEY

The 60-inch reflector of the Mount Wilson Solar Observatory was first tested visually on the stars on the night of December 13, 1908, and the first celestial photograph was secured with it on December 19. A number of accessories of the telescope and its steel dome and building still remain to be completed; the most important of these

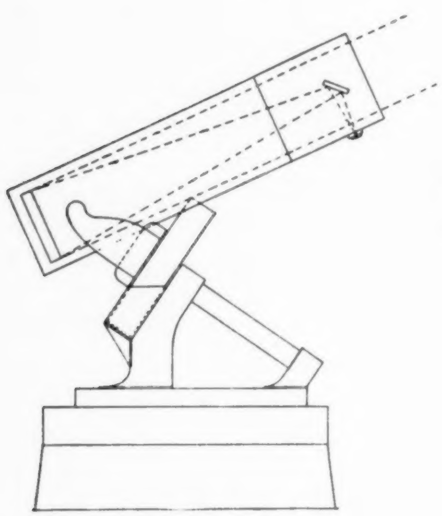


FIG. 1

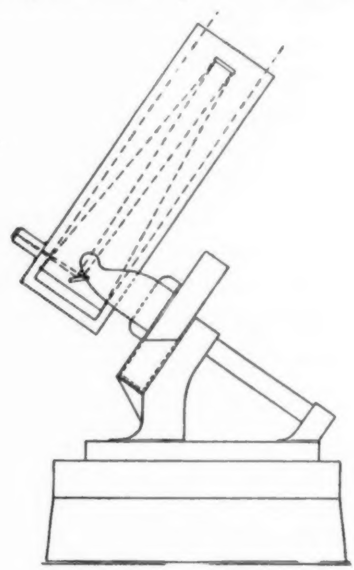


FIG. 2

are the three spectrographs, and the small refrigerating apparatus for holding the large mirror throughout the day at the expected night temperature.

The 60-inch (152 cm) reflector is designed to be used in four principal ways, as follows: First, as a Newtonian, for direct photography with the double-slide plate-carrier, and for spectroscopic work with a spectrograph carried at the Newtonian focus; in this use the focal length is 299 inches (7.6 m) (see Fig. 1). Second, as a Casse-

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 36.

grainian, for direct photography with the double-slide plate-carrier; in this use the equivalent focal length is approximately 100 feet (30.5 m), and the enlarged image is formed at the north side of the tube, near its lower end (see Fig. 2). Third, as a Cassegrainian for spectroscopic work with a large spectrograph, of the type of the Bruce spectrograph of the Yerkes Observatory, attached to the north side of the strong cast-iron part of the tube, near its lower end; in

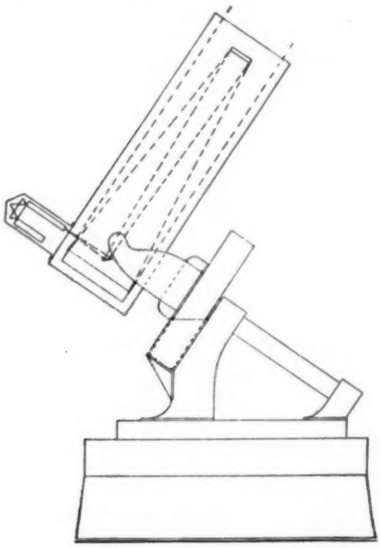


Fig. 3

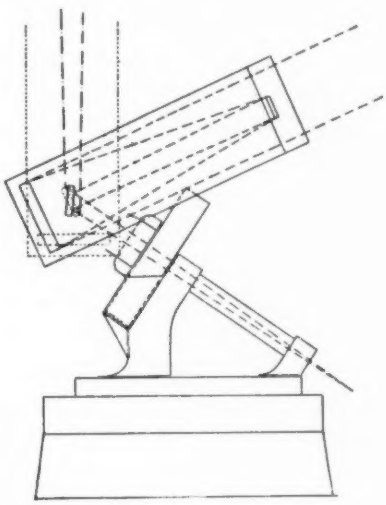


Fig. 4

this use the equivalent focal length is approximately 80 feet (24.4 m) (see Fig. 3). And fourth, as a Cassegrainian-*Coudé* for spectroscopic work with a very large spectrograph mounted on stationary piers in an underground constant-temperature pit; in this use the equivalent focal length is approximately 150 feet (45.5 m) (see Fig. 4.)

THE OPTICAL PARTS

For the above uses of the telescope six optical mirrors are required, all of which have been completed in our shop: the 60-inch paraboloidal mirror of 299 inches (7.6 m) focal length, which in its finished condition is $7\frac{5}{8}$ inches (19.4 cm) thick at the edge, $6\frac{7}{8}$ inches (17.5 cm) thick at the center, and weighs 1900 lbs. (865 kilos);

the Newtonian plane mirror, which is of elliptical outline, is $19\frac{3}{4}$ inches (50.2 cm) long, $14\frac{1}{2}$ inches (36.8 cm) wide, and $3\frac{1}{8}$ inches (7.9 cm) thick; the *Coudé* plane mirror, which is also elliptical in outline, is $22\frac{1}{4}$ inches (56.5 cm) long, $12\frac{1}{2}$ inches (31.8 cm) wide, and $3\frac{5}{8}$ inches (9.2 cm) thick; and three convex hyperboloidal mirrors, with diameters respectively of 16 inches (40.6 cm), $16\frac{3}{4}$ inches (42.6 cm), and $17\frac{1}{2}$ inches (44.5 cm), and giving equivalent focal lengths, as before stated, of approximately 80 feet (24.4 m), 100 feet (30.5 m), and 150 feet (45.7 m) respectively; each of these mirrors is about 3 inches (7.6 cm) thick. All of these mirrors are polished approximately flat on the back, and when in use in the telescope are silvered on the back as well as on the face, in order that the effect of temperature change may be symmetrical on front and back.

The methods used in grinding, polishing, and testing the mirrors are practically the same as those described in my paper on "The Modern Reflecting Telescope," published by the Smithsonian Institution in 1904. The methods used in testing the optical surfaces are also described in the *Astrophysical Journal*, **19**, 53, 1904. As these methods have now been applied and thoroughly tested in the case of a reflecting telescope of the largest size with satisfactory results, the following remarks upon the optical work may be of interest.

Of much practical importance in its bearing upon the making of very large optical surfaces is the fact that, in the case of the 60-inch glass, grinding and polishing tools of only about one-fourth the area of the glass were used with entire success in excavating the large concave and in fine grinding and polishing; a full-size, flat grinding tool was used only in the preliminary work of securing a perfect surface of revolution. A circular grinding tool of cast-iron, $31\frac{1}{2}$ inches (80 cm) in diameter, was used in all of the fine grinding of the large concave surface. In polishing this concave, and in bringing it to an optically perfect spherical surface preparatory to parabolizing, a 90° sector-shaped polishing tool of exactly one-fourth the area of the large glass was used with the best results. In parabolizing, a circular polishing tool 20 inches (50.8 cm) in diameter was exclusively used in securing the necessary change of curvature from center to edge of the glass; in addition to this the 90° sector tool, used with long diametrical and chordal strokes, was found to be of great value in smoothing out the paraboloidal surface. With these two figuring tools alone, used with the machine, a very close approximation to a true paraboloid was secured. The figuring was completed with much smaller tools used by hand to soften down several slight high zones.

In figuring the large paraboloid, one modification only was found desirable in the polishing machine described in my Smithsonian paper. The two cranks which give the motion to the polishing tools were remade in such a way that their throw or stroke can now be altered at will while the machine is running. The optician is thus enabled to change the position and stroke of the tool with a perfectly smooth progression while parabolizing; these changes are actually made at the end of each revolution of the glass, and a very great improvement in the smoothness of curvature of the paraboloid is at once apparent.

In the early stages of figuring the large paraboloid, testing was done at the center of curvature, by measuring the radius of curvature of the successive zones; in the final stages, however, all tests were made at the focus of the paraboloid, with the aid of a 36-inch (91.4 cm) collimating plane mirror of the finest figure, which was made in our optical shop expressly for the purpose of testing the large paraboloid and the three smaller hyperboloidal mirrors described above. This 36-inch plane mirror was mounted on edge on an iron carriage sliding on massive iron ways carefully finished straight, and could be moved horizontally by means of a long screw; in this manner it could be readily placed so as to show, at the testing knife-edge at the focus of the 60-inch paraboloid, any 36-inch circle of this paraboloid. This test is a most rigorous and satisfactory one, enabling the optician to see, and to determine the character of slight zonal errors which cannot be detected by the test at the center of curvature. The three hyperboloidal mirrors were tested in a similar manner, in conjunction with the 36-inch plane mirror.

While a collimating plane mirror of the full size of the paraboloid would be desirable and convenient, my experience has shown that a plane mirror with a diameter three-fifths that of the paraboloid, used as above described, gives excellent results. A rough disk of glass has accordingly been ordered for a 60-inch plane mirror for testing the 100-inch (254 cm) Hooker glass.

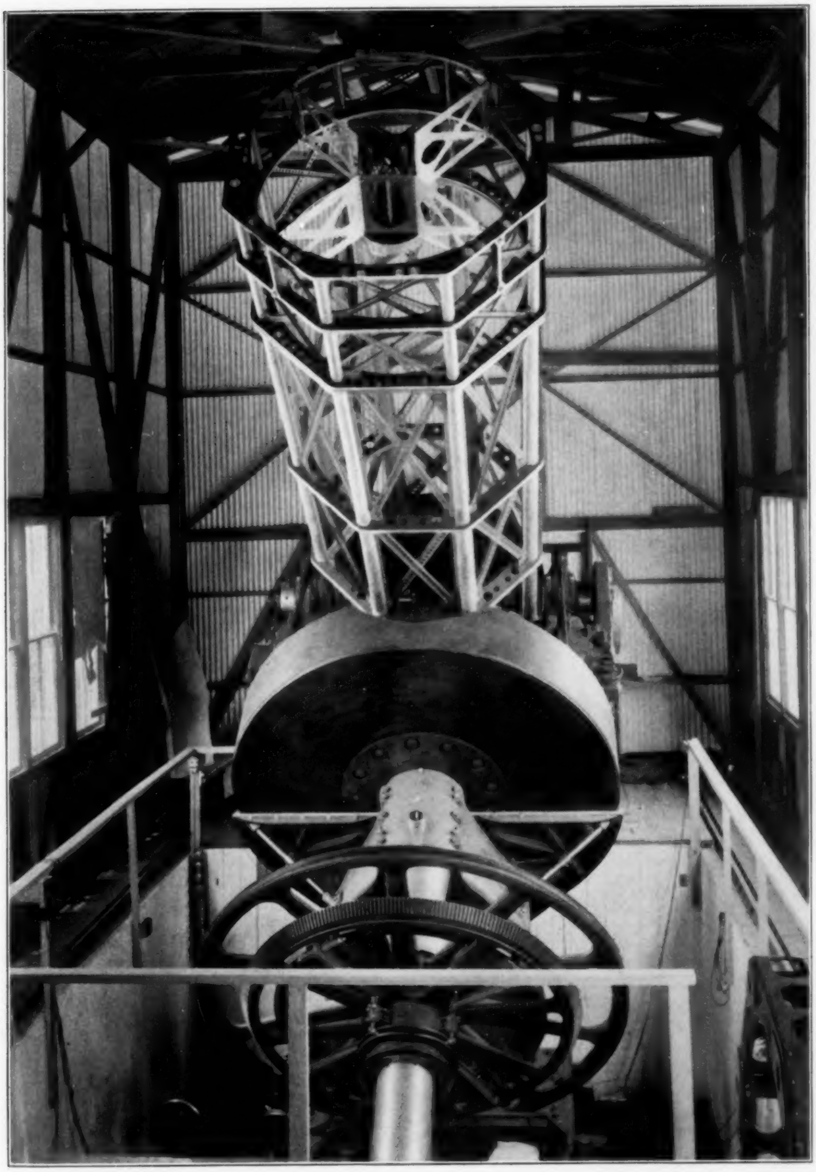
THE MOUNTING

In all essential features the design for a 60-inch mounting described in my Smithsonian paper has been carried out. The general character of the mounting will be seen by reference to Plates XVI and XVII; the first of these shows the mounting as it appeared in our erecting shop in Pasadena, the second as it appears when finally set up in its dome on Mount Wilson.

The very large parts of the mounting, including the base, the polar axis, the mercury float and trough, and the tube, were made by the Union Iron Works Company of San Francisco; a large amount of final machining and finishing of these parts was done by us after their arrival at Pasadena. In addition, the construction of all of the smaller and more refined parts of the mounting, including the driving-clock and its connections, the electric quick- and slow-motion mechanism, the lever-support system of the large mirror, the cells and their supports for the five small mirrors, the automatic-rotation mechanism for the *Coudé*-plane mirror, the large double-slide plate-carrier, the graduated circles, and the cutting and grinding of the 10-foot (3.5 m) worm-gear on the polar axis, was done at our shop in Pasadena.

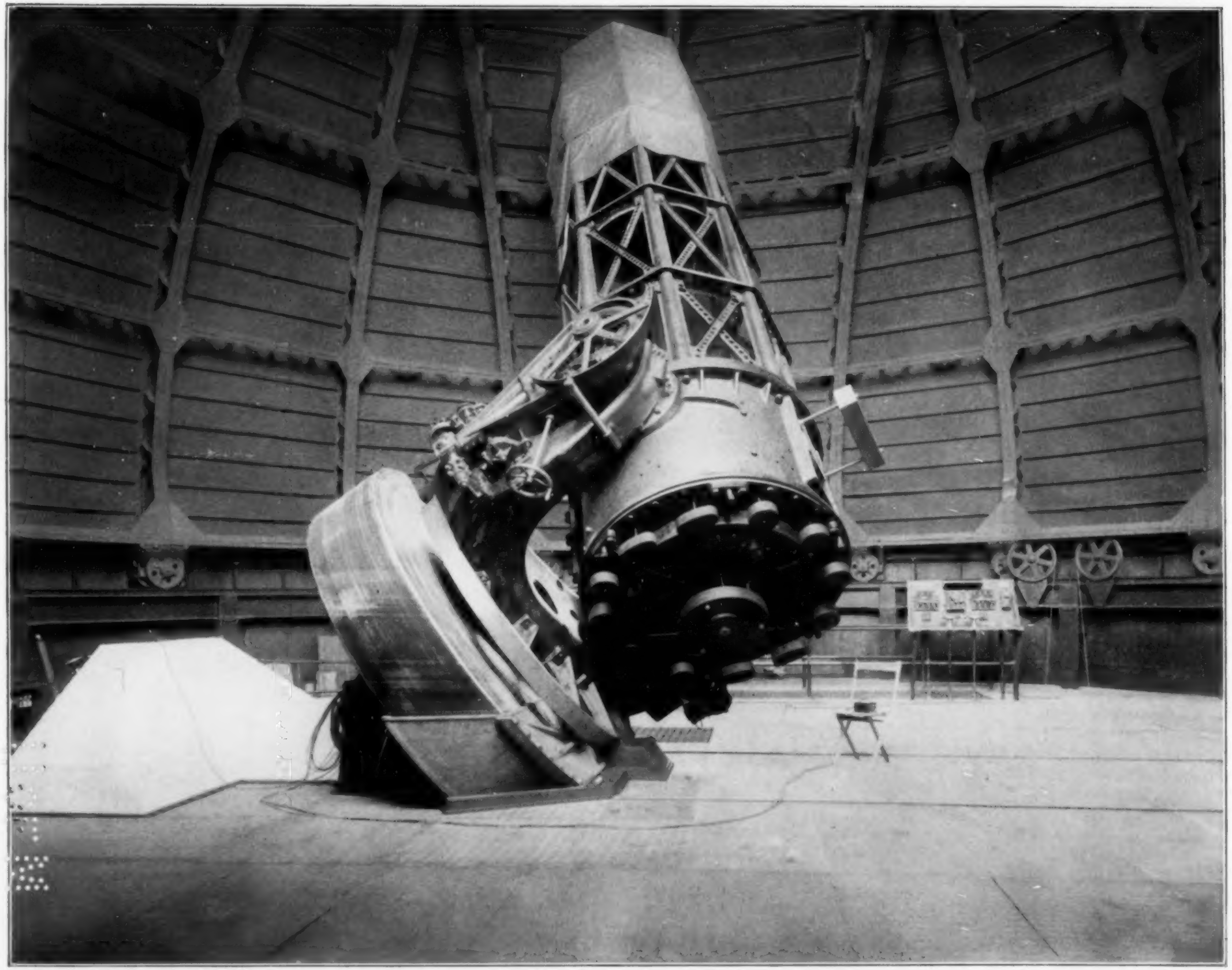
The cast-iron base is 15 feet (4.57 m) long, 7 feet (2.13 m) wide, 18½ inches (47 cm) deep, and weighs 14,000 lbs. (6350 kilos). The north and south columns, forming the bearings of the polar axis, weigh respectively 9500 lbs. (4275 kilos), and 2000 lbs. (907 kilos). The polar axis is a hollow forging of nickel-steel, hydraulic-forged by the Bethlehem Steel Company, and is turned and ground all over; it is 15 feet (4.6 m) long, varies from 15 to 18 inches (38.1 to 45.7 cm) in diameter, and weighs 9200 lbs. (4140 kilos). At its upper end is a head or flange 4½ feet (1.37 m) in diameter and 6 inches (15.2 cm) thick. To the lower side of this flange is bolted the float, which is a very rigid hollow disk of steel boiler plate, 10 feet (3.05 m) in diameter and 2 feet (61 cm) deep or thick, weighing 8600 lbs. (3900 kilos). To the upper side of the flange of the polar axis is bolted the fork, between the great arms of which the tube swings in

PLATE XVI



60-Inch Reflector Mounting in Erecting Shop

PLATE XVII



60-Inch Reflector Mounting in Dome

declination on nickel-steel trunnions 7 inches (17.8 cm) in diameter. The fork is of cast-iron, of hollow box-section, is 9 feet (2.7 m) across in extreme width, and weighs 10,400 lbs. (4711 kilos). Twelve nickel-steel bolts, 2½ inches (6.4 cm) in diameter and 3 feet (91.4 cm) long, pass through reamed holes through the base of the fork, through the flange of the polar axis, and through the cast-iron center or hub of the float, thus clamping these massive parts together with extreme strength and rigidity at a region of the mounting where the greatest tendency to flexure occurs.

The float dips in a cast-iron trough which is machined to nearly fit the float, leaving a space of only one-eighth of an inch all around; this space is filled with 650 lbs. (295 kilos) of mercury. The immersed part of the float gives a displacement of about 50 cubic feet (1.4 cu. m) of mercury, thus carrying 21½ tons (19,479 kilos) of the moving parts of the telescope in the fluid, and relieving 95 per cent. of the weight on the large bearings of the polar axis. The mounting is so designed that the center of weight of the moving parts is vertically above the center of flotation.

The large worm-gear for the diurnal rotation of the telescope is 10 feet (3.05 m) in diameter and has 1080 teeth. While being cut, these teeth were spaced with the utmost care with the aid of a 36-inch (91.44 cm) Warner and Swasey graduated circle of the finest quality. The teeth were then hobbed (with a hob of special design by which the accuracy cannot be lost) and were then ground with hone powder of finer and finer grades, with oil, and were finally polished with rouge and oil. This treatment not only eliminates any small irregularities of spacing, but leaves the teeth exquisitely smooth.

The driving-clock is in many respects a copy of the driving-clock of the 40-inch Yerkes refractor, built by Warner and Swasey. I have introduced one important modification, however, as follows: the clock-governor is driven by a weight through a spur-gear train, as usual, but the motion of the governor is communicated to the telescope through the medium of a worm and worm-gear, which are ground with the utmost care to eliminate periodic errors. This worm-gear of 80 teeth, together with the large worm-gear of 1080 teeth on the polar axis, gives the entire reduction from the clock-governor, rotating once in a second, to the polar axis, which rotates once in 24 hours. Furthermore, the two worm-gears named are the only gears used in communicating the rotation of the clock-governor to the polar axis, the driving-clock being so placed that all spur-gears and bevel-gears are dispensed with.

To relieve friction and wear on the polished teeth of the large worm-gear, and on the clock and clock-connections, the following simple expedient is used. A small wire-rope passes over a grooved wheel keyed to the polar axis, runs over two grooved pulleys on the west side of the telescope base, and is loaded with about 100 lbs. of iron weights hanging vertically on the west side of the pier. With this assistance, only about two pounds' pressure on the teeth of the 10-foot worm-gear is required to rotate the moving parts toward the west.

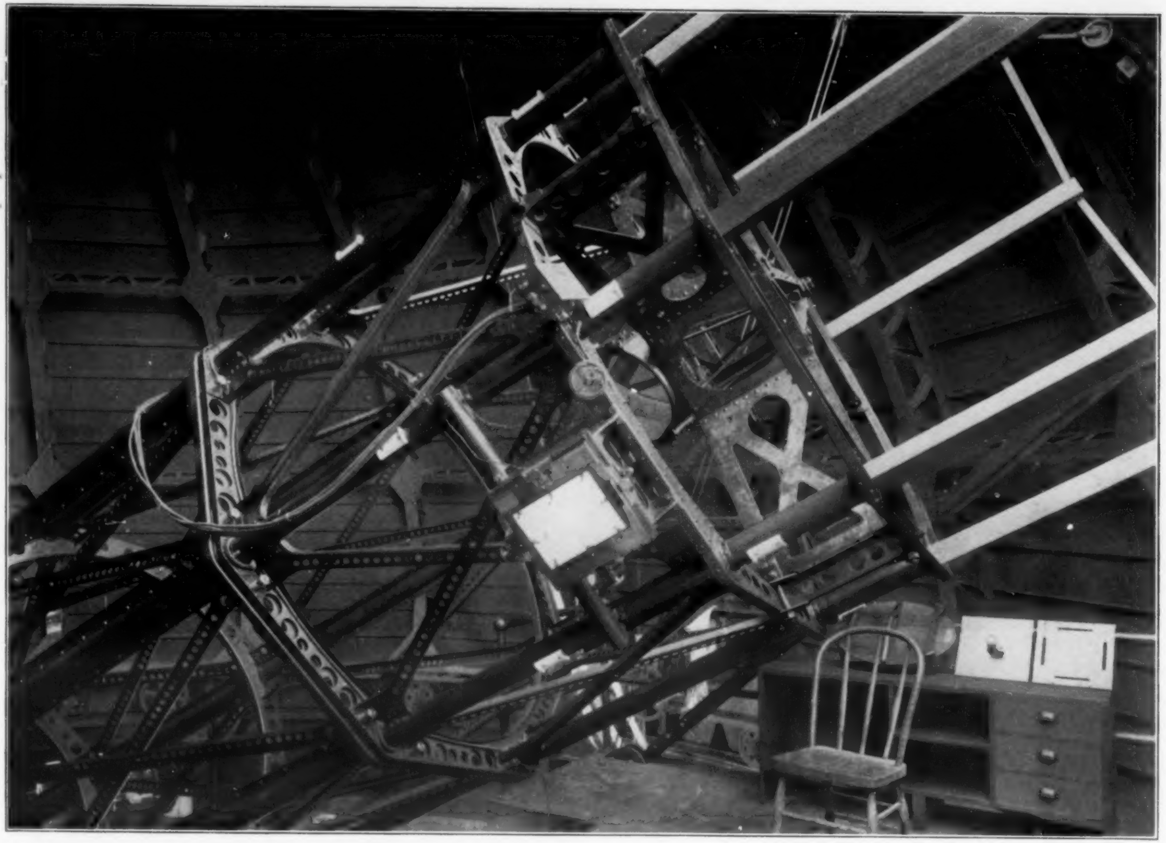
As a further means of keeping the teeth of the large worm-gear continually in the finest condition, a small motor is provided by means of which the gear and its worm can be repolished at any time. In practice this is done several times each week; the worm-shaft is disconnected from the driving-clock by simply removing two small screws, fine graphite and oil are supplied as a lubricant, and the large worm-gear and its worm are run together for an hour.

As a result of the mercury flotation and the care which has been given in finishing the driving-clock, the clock-connections, and the large worm-gear, the great telescope follows the stars with exquisite smoothness and accuracy, despite the fact that the moving parts weigh nearly 23 tons.

The telescope is provided with electric quick and slow motions. The former give a speed of 30 degrees per minute of time, in both right ascension and declination. The latter are arranged to give two speeds, one of six minutes of arc in a minute of time, for ordinary fine setting, and a slower one of one-half minute of arc in a minute of time for guiding with the spectrographs. The electric wiring is so arranged that the slow motions can be operated from several convenient points.

The octagonal skeleton tube is worthy of description because of its extraordinary rigidity. It consists of eight conical tubes of $\frac{1}{8}$ inch (3.2 mm) sheet steel, about 15 feet (4.6 m) long, tapering from 5 inches (12.7 cm) diameter at their lower ends to 3 inches (7.6 cm)

PLATE XVIII



DOUBLE-SLIDE PLATE-CARRIER IN PRINCIPAL FOCUS OF 60-INCH REFLECTOR diameter at their upper ends; each tube is made of two parts riveted together, with two flanges 135° apart extending their whole length; to these flanges are riveted the diagonal braces; three rigid rings connect the eight tubes together. Any one of four interchangeable extensions of the tube, called "cages," of similar construction, can be connected to the upper end of this permanent part of the skeleton tube; one of these carries the Newtonian plane mirror and its accessories; this is shown in Plate XVIII; each of the others carries one of the small hyperboloidal mirrors, with its cell, cell-support, and small electric motor for focusing. A simple and effective machine, called the "cage-lift," which is suspended from the framework of the dome, enables the observer or assistant to interchange the cages quickly and safely.

The Newtonian "cage" or tube-extension can be connected to the tube in four different positions 90° apart, that is, with the diagonal plane mirror and the double-slide plate-carrier facing either north, east, south, or west. The cage-lift is so designed that the tube-extension can be rotated to the position desired while suspended in it, before being attached to the tube.

The double-slide plate-carrier is most carefully designed, and is much more elaborate than those which I have made and used in the past. It is so planned that it will take either 5×7 inch (12.7×17.8 cm) or 6½×8½ inch (16.5×21.6 cm) photographic plates. This and other features of the design allow a very large range of movement of the guiding eyepiece, for choosing the most suitable guiding-star available—a matter of the utmost importance in using this attachment. Provision is made for altering the plane of the photographic plate when desired, during the exposure, without danger of relative rotation of the field and plate.

Mention should also be made of the lever-support system of the 60-inch mirror. The system fully described in my Smithsonian paper has been used without modification. The mirror is "floated" so that no flexure occurs sufficiently large to be detected by optical tests; and, in addition, the position of the mirror is defined so perfectly with reference to its tube that no wandering or jumping of the star-images, due to the slipping of the mirror in its cell, can be detected in the guiding eyepiece.

THE STEEL BUILDING AND DOME

The building which supports the dome is entirely of light steel construction. Twenty columns, each 22 feet (6.7 m) high, form the corners of the 20-sided equilateral polygon. These columns support twenty horizontal box-girders, which carry the double track upon which the dome revolves.

The building has two sheet-metal walls; the inner one is of $\frac{1}{16}$ inch galvanized sheet steel, and is planned to be air-tight; the outer wall, two feet distant from the other, is of light galvanized sheet steel, and serves merely as a sun-protection. A free circulation of air is allowed between the two; both are painted white. Sixteen sheet-metal windows, closing air-tight against heavy rubber packing, are easily accessible from the lower floor, and assist in ventilating the building and dome quickly when desired.

The ground floor of the building is of cement; on this floor are the dark rooms and the electric machinery for revolving the dome. Nineteen feet above this is the operating floor, of thin checkered steel plate supported by light steel columns and I-beams. From this floor are operated the dome-drive machinery, the dome-shutter, the wind-screen, the quick and slow motions of the telescope, the right ascension and declination clamps, etc.; from this floor also the right ascension and declination circles are read. On this floor are arranged the silvering carriage (which is necessary when removing the large mirror from the tube, and when silvering it) and the interchangeable ends of the tube which are not in use on the telescope. In this floor are twelve large trap-doors, $3\times7\frac{1}{2}$ feet (0.9×2.3 m) in size, which can be quickly opened to assist in ventilating the building and dome.

The dome is 58 feet (17.7 m) in diameter, and is of light steel construction with sheet-metal covering, coated inside with granulated cork, to prevent dripping from condensation of moisture, and painted white outside. It revolves on double tracks which are machined true, the dome wheels being all double, conical, and furnished with the best Hess-Bright ball-bearings. The dome moves with great smoothness. Two motors are used in turning it: one of three horse-power, which is so geared that the dome makes one complete revolution in six minutes; and a one-horse-power motor,

PLATE XIX

Steel Building and Dome for 60-Inch Reflector which drives a variable-speed machine, by which the speed of the dome can be changed at will (by simply turning a hand-wheel) to any point between one revolution in one hour and one revolution in twenty-five hours; this allows the observer, when working on the observing platform attached to the dome, to be moved with exactly the right speed to compensate for the horizontal component of the motion of the telescope.

The dome-shutter is extremely large, having a clear opening 16 feet (4.9 m) wide. Instead of opening horizontally in halves, the shutter runs back over the dome, as shown in Plate XIX; it is opened and closed by a six-horse-power electric motor. A large metal door, below the shutter opening, 17 feet (5.2 m) long by 8 feet (2.4 m) high, turning outward on hinges at its bottom, can be opened when it is necessary to observe objects near the horizon.

A light metal observing platform, 17 feet (5.2 m) long by 9 feet (2.7 m) wide, travels up and down the curve of the shutter opening, by means of a three-horse-power electric motor. This platform can be operated either from the operating floor or from the platform itself, by simply pushing a button; it is so designed that it automatically remains horizontal in all positions. In addition to its vertical movement, and its horizontal movement with the dome, the platform can be moved about 30 inches (76.2 cm) radially with respect to the vertical axis of the dome. This combination of motions enables the observer to reach the upper end of the tube, and to work with the telescope as a Newtonian, with the utmost convenience, in most positions of the telescope.

A wind-screen 17 feet (5.2 m) wide by 35 feet (10.7 m) long is provided, which can be quickly raised and lowered in the shutter opening by suitable mechanism; it is made of heavy black canvas supported on large steel tubes with rollers at their ends. This protects the telescope from wind, and also from lights in the valley.

As will be seen in Plate XIX, the exterior of the dome is covered with a strong frame-work of steel pipe. This will be covered during the spring, summer, and fall with gores of white canvas, laced on, at a distance of about two feet from the sheet-steel covering of the dome; provision is made for ample circulation of air beneath the canvas. This, together with the white outer wall of the building below, affords a complete sun-protection for the building and dome.

Furthermore, the entire building and dome are planned to close air-tight. For this purpose a frictionless water-seal is provided at the junction of the building with the dome; and all outside doors and windows close tightly against heavy rubber packing. The dome-shutter also is lined all around with air-tight cushions which can be pressed tightly in place by means of two levers operating a series of toggle-joints. In the early morning, after a night's work, the dome and building will be closed, not to be opened until after sunset, and thus a great volume of 120,000 cubic feet (3360 cu. m) of cool night air will be shut in air-tight. It is believed that this provision, together with the complete sun-protection of the dome and building, will reduce the rise of temperature within the structure during the day to a very few degrees. This protection from daily temperature changes should be sufficient for the telescope mounting and for the smaller mirrors. To further protect the large mirror during the day, a small refrigerating plant will be installed within a few months, which will supply constant-temperature air, at the expected night-temperature, circulating through a jacket inclosing the entire lower end of the telescope tube. The necessity for this protection of the large mirror from the daily rise and fall of temperature, to preserve the finest optical figure, was fully demonstrated by a long series of experiments in the optical shop with this mirror after its completion.

It will be seen also that a serious effort has been made in the design of the dome and building to eliminate the so-called dome- and building-effect, that is, the local effect upon atmospheric definition caused by heat-radiation from, or air currents in, the dome and building, which is often a most serious detriment to the successful performance of large telescopes. An hour after sunset the 16 ventilating windows near the lower floor of the building, the 12 trap-doors in the operating floor, and the great dome-shutter, the latter having an opening 16×45 feet (4.9×13.7 m) in size, are all opened, and the light metal columns, girders, and walls, inside and outside, quickly assume the temperature of the night air. The ventilating doors and windows are then closed, to prevent draughts. The very fine definition which we have already had on Mount Wilson with the 60-inch aperture, even on winter nights, indicates not only that the provisions just described are highly effective, but that the general atmospheric conditions at night on the mountain will prove sufficiently good for this and even larger apertures.

In this brief description of the new reflector and its accessories, I have called attention chiefly to those refinements and special features which, in designing the instrument, have appeared to me necessary. Mere bigness is no criterion of efficiency; if a great telescope is to yield a gain in results even approximately proportional to its increase in size, the utmost care must be given to meeting all those conditions which experience in the use of large telescopes has shown to militate against their successful performance. It was a most serious question whether it would be possible to give as fine a figure to the 60-inch mirror as was attained in the case of the 24-inch Yerkes mirror; the difficulties were of course incomparably greater, but the final figure of the 60-inch is decidedly better than that of the smaller mirror, and it is confidently expected that the temperature control will enable it to remain so while the telescope is in use. Similarly, it was a serious question whether the moving parts of the 60-inch telescope, weighing 23 tons (20,838 kilos), could be made to follow the stars as smoothly as those of the 24-inch, which weigh one ton (907 kilos); such smoothness of following is of course necessary for the finest results in photography; and it must be remembered that much greater smoothness and accuracy of motion are actually required in the large instrument, on account of its greater focal length and magnifying power. It is therefore a great satisfaction to see the star in the guiding eyepiece of the 60-inch remain perfectly bisected on the spider-lines for several minutes at a time, without perceptible tremor, and in addition, frequently to see the image of the guiding star itself, even with winter conditions, as small and sharp, and with its diffraction pattern as clearly cut, as I have ever seen in the 24-inch at Yerkes.

For the successful performance of the new reflector, special credit is due to Mr. Jacomini, foreman of the instrument shop of the Observatory; to Mr. Barnes, Mr. Schrock, and Mr. Kinney, for their great care and skill in the optical work, and to Mr. Dowd, for the installation of the complicated electrical work of the telescope mounting and dome.

I am indebted also to Director Hale for the opportunity afforded me to carry out in their entirety my plans for the great reflector and its dome, building, and accessories.

JANUARY 7, 1909

THE ULTRA-VIOLET ABSORPTION SPECTRA OF CERTAIN METALLIC VAPORS AND THEIR MIXTURES

By R. W. WOOD and D. V. GUTHRIE

It has been found by one of the present writers that the absorption spectrum of a substance in the state of a vapor may be modified by the presence of another gas or vapor, in such a way as to indicate that there is some interaction between the molecules. In the case of iodine vapor[1] mixed with the vapor of ether or bisulphide of carbon of a given density, if the iodine is not present in excess we have the absorption spectrum which is characteristic of iodine solutions, i. e., a broad band which obliterates the blue-green and violet region. If a little more iodine is added we get at once the absorption spectrum of gaseous iodine, a spectrum containing hundreds of fine lines in the orange and yellow region. In other words, a given quantity of ether vapor of a given density is able to dissolve a given quantity of iodine, any excess of the latter substance existing in the gaseous state, that is, with its molecules unaffected by the other vapor.

A phenomenon of a different nature has been observed in the case of mercury vapor,[2] which has a strong absorption band at wavelength λ 2536. If the vapor is evolved in a vacuum, this band broadens rapidly on the less refrangible side, attaining a width of three or four hundred Angström units. There is little or no broadening in the other direction. If air, hydrogen, helium, nitrogen, or some other inert gas is present, the band broadens symmetrically at first, and, after acquiring a certain width, continues to increase only in the direction of longer wave-lengths.

The marked unilateral broadening of the mercury band is in itself a point of interest, and has been recently discussed by Larmor,[3] who suggests that the unsymmetrical nature of the band may be due to the formation of loose molecular aggregates, which on account of mutual influence tend to vibrate in longer periods, and so give rise to the displaced part of the band. Another interesting case of this

[1] Wood, "Absorption Spectra of Solutions of Iodine and Bromine above the Critical Temperature," *Phil. Mag.*, **41**, 423, May 1896.

[2] Wood, *Astrophysical Journal*, **26**, 41, 1907.

[3] *Astrophysical Journal*, **26**, 120, 1907.

kind is described by Lyman,[1] who finds an absorption band for oxygen in the extreme ultra-violet, which exhibits markedly unsymmetrical broadening. He applies Larmor's explanation to this band, observing that the conditions demanded by the theory exist in the case of oxygen. Since absorption bands of this character possess much interest, it is important to find whether they exist in case of other metallic vapors besides that of mercury.

OBJECTS OF INVESTIGATION

The present investigation was undertaken with the following objects in view.

1. To obtain the absorption spectra of certain metallic vapors, particularly in the ultra-violet region of the spectrum, where they have not been studied heretofore.

2. To observe the manner in which the absorption bands of each metal behave with increasing vapor-density.

3. To determine whether the absorption bands are affected in any way by the presence of a foreign substance.

APPARATUS AND METHODS

A small quantity of the metal to be studied was placed in a quartz bulb of 10 or 15 cc capacity, which was then exhausted and sealed. Quartz furnishes a very efficient material for use in examining the absorption of metals which volatilize at a temperature only moderately high, for, in addition to its transparency to ultra-violet light, it does not soften in the hottest flame of the ordinary blast lamp and so can withstand great pressures of the inclosed vapor. Prolonged heating of the bulbs in the flame of the Bunsen burner causes them to become incrusted on the outer surface with a material which was quite opaque to the shorter wave-lengths, apparently due to a sort of devitrification of the quartz. This could be removed, however, and the transparency of the bulb restored, by heating it to the softening point for a short time in the oxy-hydrogen flame.

As a source of light, a spark discharge between cadmium electrodes was used, a Leyden jar or a condenser being placed in parallel with the secondary circuit. This source furnishes a strong and fairly uniform continuous spectrum in addition to the scattered lines.

[1] *Astrophysical Journal*, **27**, 87, 1908.

Whenever practicable the bulb was placed in a small air bath, formed of a piece of iron tubing not much greater in diameter than the bulb, with small holes cut in the sides to permit the light to pass through it. To determine the temperature in the air bath, a platinum-rhodium thermo-couple connected with a galvanometer reading the temperature directly up to 1400° was used. The highest temperature that could be secured in the air bath, heating it with two large burners with strong air blast, was about 700°, so when higher temperatures were necessary the bulb was heated directly in the flame of the burner or blast lamp.

In part of the work a quartz lens was used to bring the light from the spark, after passing through the quartz bulb, to a focus on the slit of the spectrograph, but usually it was found advisable to pass the light of the spark directly through the bulb into the instrument, the spark being distant 12 or 15 cm from the slit, and the quartz bulb about half-way between the two. The instrument used to photograph the spectra was a small quartz spectrograph. A device attached to the plate-holder enabled it to be raised by successive steps, so that the spectra could be photographed in succession as the temperature was raised and the vapor-density increased. The plates used were Seed's 26. The range of the spectrum which could be investigated extended from about λ 5200 to λ 2150.

OBSERVATIONS AND RESULTS

1. *Cadmium.*—Two absorption lines were found for cadmium, corresponding to the emission lines λ 2288.1 and λ 3261.2, the former being much the more prominent. As the vapor in the bulb increases in density the emission line of the spark λ 2288 appears bisected by a fine dark line, the widening of which finally obliterates the bright line entirely (Fig. 1). The dark band eventually attains a width of nearly 200 Å. U. The other absorption line makes its appearance in a different manner. There are two bright lines in the *Cd* spark spectrum at wave-lengths 3251 and 3261. As the vapor in the bulb increases in density the latter bright line gradually fades away, disappearing entirely at one stage. Its place is then taken by a dark line, which, however, never becomes very broad with the vapor-densities used in the present work. This apparent difference in the manner in which

the absorption line makes its appearance is, without doubt, to be attributed to the smaller dispersion of the quartz spectrograph for this region of the spectrum.

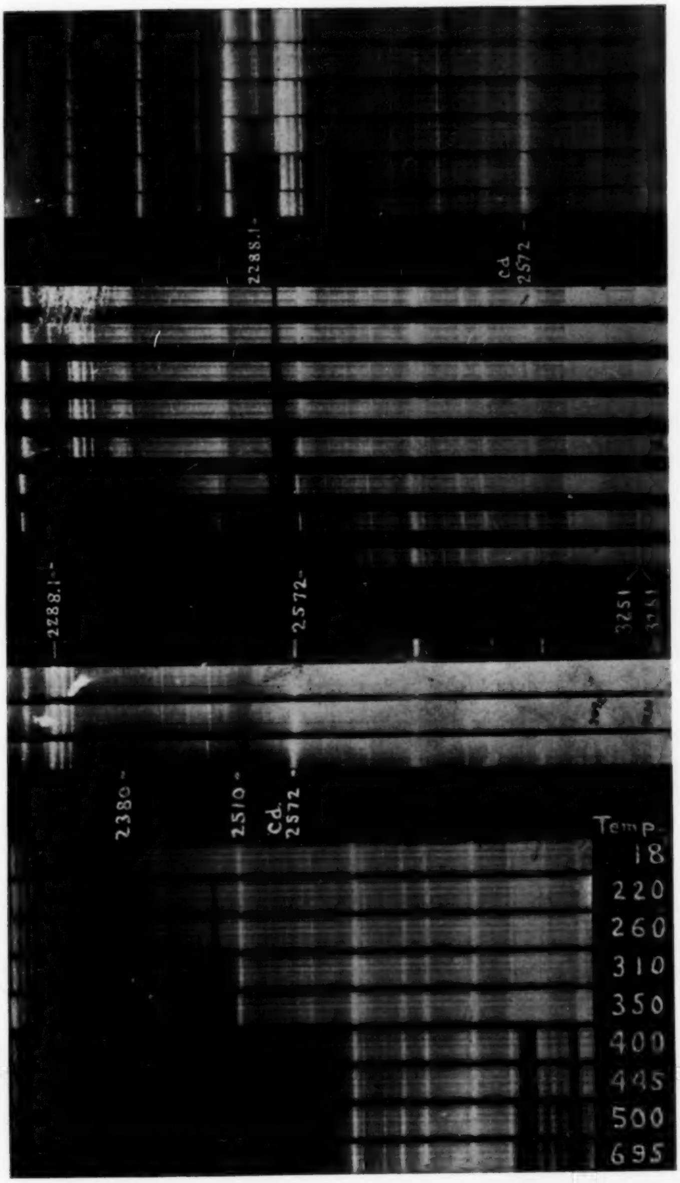
The absorption is relatively weaker than that of the line λ 2288, for the bright line λ 3261 is not obliterated until the λ 2288 line has attained the width shown in the lower two spectra of Fig. 1, Plate XX. The line λ 3261 is not shown in this figure, but it appears in Fig. 2. These two lines are the only ones in the cadmium spectrum which show any trace of absorption, though vapor of such density has been used that the line at λ 2288 broadened nearly to the cadmium line at λ 2572.

The manner of broadening of the absorption bands with increasing vapor-density was then studied. It was found that in a vacuum, no foreign substance being present with the cadmium, the band λ 2288 broadens perfectly symmetrically, the broadening amounting to considerably more than 100 Å. U. on each side at the highest temperatures employed. It was found, however, in working with zinc in which a little cadmium was present as an impurity, that when mercury was added, this absorption band appeared to broaden only on the side toward the longer wave-lengths.

In order to determine whether this was really an effect of the mercury upon the cadmium, a bulb was prepared containing cadmium and a little mercury. In this case there was a marked unsymmetrical broadening of the absorption band at λ 2288 (Fig. 2). The band broadens a little on the more refrangible side, especially at the higher temperatures, but very much more on the less refrangible side. The emission line *reverses on the less refrangible side* first, instead of in the center as before, and the absorption band has extended almost as far as the emission line λ 2307 by the time the more refrangible edge of the emission line λ 2288 has entirely disappeared (Fig. 2). Mercury vapor, even when very dense, shows no absorption band at this point, though there is a fairly strong band at λ 2338 and another very broad one at λ 2140. Measurements on one of the negatives in which the band had attained a considerable width gave the following result:

More refrangible limit...............	λ 2415.1
Less refrangible limit...............	λ 2270.6
Mean........................	λ 2342.9

PLATE XX



1

2

3

6

λ 2510 Hg 2536 2768 3092 3230

showing that an apparent shift of the mean wave-length of the band from the position of the emission line (λ 2288.1) amounting to about 55 Å. U. has taken place. Similar measurements on negatives representing the absorption of pure cadmium showed that the distance of each limit of absorption from the emission line was the same, to within the limit of error of observation. The shift is of course only apparent, for the densest or heaviest part of the band remains in the position of the emission line.

This effect is all the more remarkable in that it forms a contrast to the behavior of the mercury band at λ 2536, which broadens unsymmetrically in vacuo, but symmetrically when a foreign gas is present. However, this effect, as clearly as that, affords an instance of a modification in the appearance and position of an absorption band of one substance resulting from the direct influence of a foreign substance. The absorption line at λ 3261 does not appear to be affected, showing no signs of asymmetry in either case. Its width, however, at the temperature available was too slight to enable any very definite conclusion to be drawn as to the effect of the mercury vapor upon it. It can be seen in the two lower spectra of Fig. 2. The gradual disappearance of the bright line does not show well in the enlargement. The spectrum in which it has just disappeared is marked with an *x*.

2. *Thallium.*—The absorption of thallium vapor was next investigated. It was found that when pure thallium was sealed up in an exhausted bulb and its absorption examined, three or four faint absorption bands were to be seen, appearing at about 400° and not becoming strong even at the highest temperatures. When now a little mercury was added to the thallium, and its absorption studied under the same conditions, a number of other absorption lines were brought out which did not appear at the highest temperatures with the pure thallium, while of the absorption bands obtained with the thallium alone, all except one *disappeared.* Thus the appearance of the absorption spectrum is entirely changed by the addition of the mercury. Further, it was found that the relative intensities of the absorption bands and the temperatures at which they first appear vary in a remarkable manner with the relative proportions of mercury and thallium.

The spark spectrum of thallium was photographed and most of the absorption lines were found to correspond to emission lines, though there were a few which did not appear to coincide with any line in the spark spectrum. The absorption bands obtained with the pure thallium were (see Fig. 3):

a) A fairly sharp but faint absorption line corresponding to the emission line λ 2380. This is the only absorption line which appears under all conditions, both with and without the addition of mercury. In the present case, with pure thallium, it never became strong, even at the higher temperatures.

b) A broad and faint absorption band lying very near the emission line λ 2530.0 on the side of shorter wave-lengths. Its mean wave-length was about 2510.

c) A band resembling the last but even fainter, and bordering on the emission line at λ 3092 but lying on the less refrangible side of this line.

d) A group of three lines, faint and not very sharp, lying very close together and uniformly spaced. The middle component coincides with the emission line at λ 3230.

Though these bands appear at a comparatively low temperature (about 400°) they change very little either in width or intensity as the temperature is further increased, a circumstance which suggests that they may be due to some easily volatilized impurity.

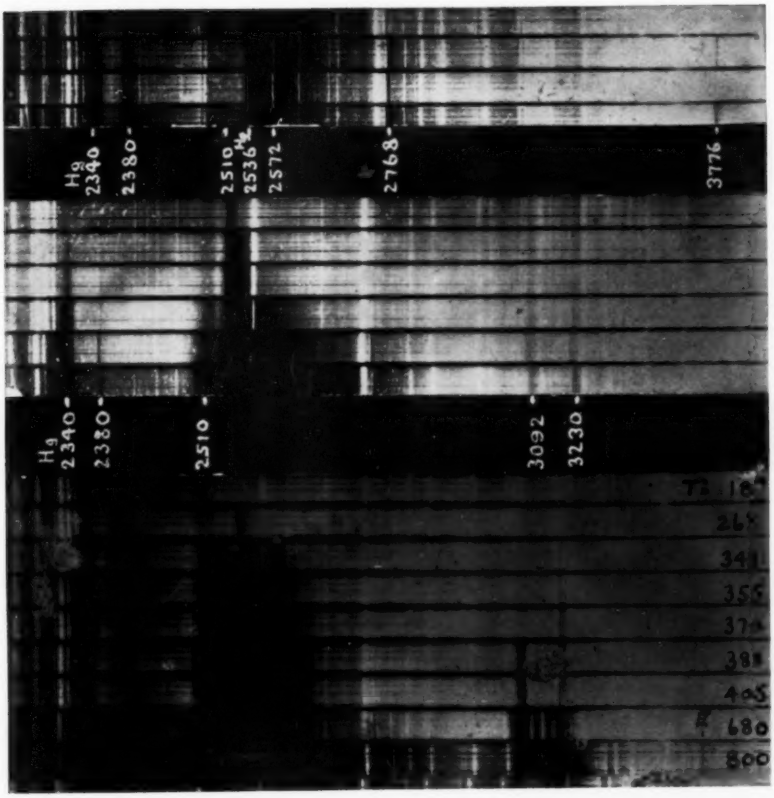
Some preliminary experiments with bulbs containing different proportions of thallium and mercury showed that with these mixtures absorption could be obtained in the case of several other lines, appearing at different temperatures in the different cases. In order to study the phenomenon quantitatively, a series of bulbs was examined containing definite amounts of thallium and mercury. First, 150 mg of thallium was weighed out and inserted in a bulb of about 10 cc capacity. Then, the amount of thallium being kept constant, six different amounts of mercury varying from 6 to 150 mg were tried with it. In the first case, although the amount of mercury was very small, the mercury absorption band at λ 2536 remaining quite narrow at the highest temperatures, this small quantity of mercury was sufficient to affect the absorption very markedly, bringing out very clearly absorption lines corresponding to the emission lines at λ 2580, λ 2768, and λ 3776 (Fig. 4, Plate XXI), and causing all the absorption bands found with the pure thallium except the one at λ 2380 to disappear.

PLATE XXI

4

5

7



λ 2510 *Hg* 2536 2768 3092 3230 3776

Absorption in the case of the line λ 2580 can be seen only when the amount of mercury in the bulb is small, for owing to the proximity to the mercury band λ 2536 it is hidden by the broadening of this band unless the band remains quite narrow. Previous experiments made by one of us have shown that the mercury band at λ 2536 even with very dense vapor expands only a few Ångström units on the short wave-length side, unless air or some other gas is present in which case it may extend almost as far down as the thallium band at λ 2510. With thallium and mercury, it apparently extends much farther down the spectrum; this change is only apparent, however, for we are dealing with two bands which fuse together when the vapor mixture is dense. The thallium band at λ 2510 broadens symmetrically, while the mercury band at λ 2536 broadens only on the side of longer wave-lengths. There are also indications, at high temperatures, of absorption corresponding to the line λ 2237.9 in one or two instances, when the amount of mercury present is small, this part of the spectrum being also obliterated in other cases by the strong absorption of mercury in the extreme ultra-violet. As the amount of mercury was increased, up to a certain point the absorption lines appeared at successively lower temperatures. Thus for the two cases where the amounts of mercury were 6 mg and 25 mg, the ratios of the amount of mercury to the amount of thallium being 1:25 and 1:2, the temperatures at which the absorption lines could be first detected were as follows:

Ratio *Hg* to *Tl*	λ 2380	λ 2580	λ 2768	λ 3776
1:25.........	600°	900° (est.)	600°	900° (est.)
1:2..........	400	700	400	500

The temperatures given are those of the air bath as indicated by the thermo-couple, except those over 700°, when the bulb was heated in the flame and the temperature estimated. For intermediate amounts of mercury the temperatures at which absorption appeared lay between these limits. As the proportion of mercury is still further increased beyond that in the second case above, the absorption lines do not appear at temperatures any lower than these.

This effect of mercury in bringing out absorption lines of thallium, which do not appear when pure thallium is examined under the same conditions, appears to be quite analogous to some observations of Liveing and Dewar (*Proc. R. S.*, **27**, 132, 350, 1878), who found that the red line of lithium, λ 6103, could be obtained reversed only when both sodium and potassium were present. They found also, in studying the absorption of magnesium, that when sodium was present, a line at λ 5300 could be seen reversed and when potassium was present, two lines, at λ 6580 and λ 6475, these absorption lines being obtainable only with the mixtures. They suggest that

a very slightly volatile vapor may be diffused in an atmosphere of a more volatile metal, so as to secure a sufficient depth of vapor to produce a sensible absorption. This would be analogous to well-known actions which take place in the attempt to separate organic bodies of very different boiling points by distillation, where a substance of high boiling point is always carried over, in considerable quantity, with the vapor of a body boiling at a much lower temperature.

It seems quite probable that something of this kind occurs in the present case.

It has been mentioned that in the series of experiments just described in which 150 mg of thallium was used in the bulb and the amount of mercury varied, all of the absorption bands found with the pure thallium except λ 2380 disappear. The amount of mercury was now kept constant (about 150 mg) and the amount of thallium varied. The surprising result was obtained that as the amount of thallium in the bulb is increased above the amount used before, these absorption bands, which had disappeared in the former case, reappear, and as the amount of thallium is still further increased, they finally become very much stronger than with the pure thallium (Fig. 5 shows this effect). The most remarkable result was obtained with a bulb containing a large amount of thallium (Figs. 6 and 7). The bands just mentioned appear in this case at between 300° and 350°, being faint at first but rapidly becoming stronger, and finally at 400° and higher becoming very broad and intense, being almost as prominent as the mercury bands. The temperatures are recorded in the figures.

The circumstance which strikes one as most remarkable is that when there is but a small amount of thallium present (Fig. 4) the absorption lines at λ 2768 and 3776 are very conspicuous, while there is no trace of the strong bands λ 3092 and 3230. With a large amount of thallium we have the latter bands very conspicuous and little or no trace of the former (Figs. 5, 6, and 7). This is especially noticeable in Fig. 7, in which the line at λ 3776 only appears in the lowest spectrum obtained at a temperature of about 800°. Whether this is a matter of the solution of thallium vapor in the vapor of mercury is a question. At the temperatures used it must be remembered that only a very minute proportion of the total amount of thallium present is vaporized in any case.

In addition to the bands which appeared in former cases, there are, in this case (Figs. 6 and 7), two strong bands lying between the bands at λ 3092 and the triplet at λ 3230, of which there were perhaps faint traces with the pure thallium, and also a number of fine lines lying near the band at λ 3230 on the less refrangible side, which are not represented on any of the former negatives. The wave-lengths of these absorption bands were measured. It was not possible to determine them very accurately, but the values given are correct to within a few tenths of an Ångström unit. For the two wider bands the limits of absorption were measured, while for the finer ones a setting was made on the middle of each, the average width being about 3 Å. U. The temperature in this case was 700°. The values obtained are as follows:

Limits of Absorption	Mean
3145.9 3166.6	3156.3
3179.1 3197.9	3188.5

Mean Wave-Length (width about 3.0)

3267.9	3308.4
3279.7	3320.5
3289.4	3337.6
3297.4	3350.1

None of these absorption bands corresponds to any emission line. The triple-line at λ 3230 appears shortly before the other bands, the most refrangible component being the strongest at first, though this is not the one that coincides with an emission line. The three lines merge into one and appear as a strong band at about 700°. The positions of the edges of these lines and of the band at λ 3092 were also measured at different temperatures, the values obtained being as follows:

	Limits of Absorption	Mean
350°	3220.2 – 3224.0	3222.1
	3228.4 – 3231.5	3229.9
	3236.8 – 3239.8	3238.3
400°	3220.2 – 3225.7	3223.0
	3228.4 – 3233.4	3230.9
	3236.8 – 3241.6	3239.2
700°*	3218.2 – 3262.1	3240.2

* The three merged into one.

It will be observed that when the lines first appear, the middle component of the triplet coincides with the emission line at λ 3229.9, and that with increasing temperature they broaden at first only on the less refrangible side, though after merging into a wide band a slight extension toward the side of shorter wave-lengths is perceptible. For the band near λ 3092 the following values were obtained:

	Limits of Absorption	Mean
400°	3091.9 – 3126.3	3109.1
700°	3081.3 – 3134.6	3108.0

It is to be noticed that the band when it first appears just touches the position of the emission line at λ 3091.9 on its more refrangible edge, broadening, however, so as to cover it, the broadening being probably symmetrical.

The manner of broadening of the thallium absorption bands with increasing vapor-density was also investigated. Difficulty was experienced in getting the absorption bands to broaden sufficiently to draw definite conclusions as to their behavior, but finally on heating one of the bulbs containing thallium and mercury in the hottest flame of the blast lamp, some of the bands brought out by the mercury attained a width of 15 or 20 Ångström units. The broadening of the bands λ 2768 and λ 3776 was found to be quite unsymmetrical, the extension on the side of longer wave-lengths being very much greater than on the opposite side, like that of the mercury band λ 2536, though not so marked as in that case. The appearance of these bands as they broaden also resembles that of the mercury band, as the limit of absorption remains very sharply defined on the more refrangible edge, but becomes very hazy and ill defined on the other side, on which the extension mainly occurs. This can be seen in Fig. 4. The line λ 2380 appears to broaden symmetrically. As already mentioned in a former part of the work, the lines at λ 3230 broaden toward the less refrangible side, while the wide band near λ 3092 probably broadens symmetrically.

The following measurements of the wave-lengths of the limits of absorption for the bands λ 2768 and λ 3776 clearly indicate the unsymmetrical character of the broading for these wave-lengths. The observations are taken at three successive temperatures, the lowest being well above 700° and the highest in the hottest blast-lamp flame. They are estimated as 800°, 900°, and 1000°.

Temperature	Edges of Band	Mean	Emission Line at
800°	2767.2 2769.1	2768.2	
900°	2766.5 2777.3	2769.9	2768.1
1000°	2765.4 2779.2	2772.3	
800°	Just visible	3775.9	
900°	3773.6 3779.3	3776.5	3775.9
1000°	3772.4 3786.3	3779.4	

As the unsymmetrical broadening of the cadmium band λ 2288 is caused only by the addition of mercury, it would be interesting to observe the behavior of these thallium bands with the pure thallium, but at the temperatures which could be attained in the present work it was not possible to obtain these absorption bands except when mercury was added to the thallium.

It was thought possible that cadmium, which volatilizes at a much lower temperature than thallium, might have the same effect as mercury in bringing out thallium absorption bands, and so a mixture of thallium and cadmium was examined for absorption. The absorption of neither substance was modified by the presence of the other, however, the thallium absorption being the same as with pure thallium and the cadmium band λ 2288 broadening symmetrically and not showing the peculiar unsymmetrical effect caused by the addition of mercury.

Observations were also made to ascertain whether the addition of mercury to sodium has any effect upon the temperature at which the D lines appear in the absorption spectrum. For this purpose pure sodium and several mixtures of sodium and mercury in different proportions were sealed up in exhausted glass bulbs and the light from a carbon arc, after passing through the bulb contained in an air bath of which the temperature could be observed, was received on the slit of a spectroscope. No effect was observed, however, the temperature at which the D lines first appeared as absorption lines being practically the same in all cases.

3. *Other metals.*—The absorption of zinc was examined both with and without the addition of mercury. In no case did any trace of absorption appear in the region of the spectrum investigated, although zinc volatilizes at a much lower temperature than thallium. It seemed probable that results might be obtained with magnesium, which also volatilizes at a comparatively low temperature, and has several lines which are often seen reversed, but when heated the magnesium attacked the surface of the quartz, rendering it opaque, and making it impossible to work with this metal. The absorption of magnesium vapor was then investigated by passing the light of the cadmium spark through the vapor contained in a long porcelain tube, the ends of which were closed by quartz plates, which was heated by means of a Heraeus electrical furnace. Rather strong absorption was found corresponding to the emission line λ 2852.2, but nowhere else in the spectrum. In particular, visual observations revealed no trace of absorption for the lines of the *b* group, even at the highest

temperatures, which were probably well above 1000°. The influence of mercury was investigated, but its presence was found to have no effect on the absorption of the magnesium vapor.

The absorption of tin, of lead, and of bismuth was also investigated. As these metals volatilize at a higher temperature, though still lower than thallium, a little mercury was added in each case with the idea that it might help on absorption, as with thallium. No absorption was observed, however, with any of these metals.

SUMMARY OF RESULTS

The results of the foregoing investigation may be summarized as follows:

1. The absorption of cadmium vapor in the ultra-violet region of the spectrum was investigated and two absorption bands were found, one corresponding to the emission line at λ 2288, the other to λ 3261. Of these the former is much the more prominent.

2. The cadmium absorption band λ 2288 was found to broaden perfectly symmetrically when the pure cadmium was examined, but when mercury was added showed a marked asymmetry, broadening much more on the less refrangible than on the opposite side.

3. The absorption of thallium vapor was investigated, and with the pure thallium four absorption bands were found, two corresponding to the emission lines at λ 2380 and λ 3230 respectively, one lying near λ 2530, on the more refrangible side, and one lying on the less refrangible side of λ 3092.

4. With a moderate amount of thallium in the bulb all these bands (except λ 2380) disappear when mercury is added, but as the quantity of thallium present is increased they reappear, and finally become much stronger than with the pure thallium. On adding mercury other bands also appear which are not found with pure thallium. Among these are bands corresponding to emission lines at λ 2580, λ 2768, and λ 3776.

5. The behavior of these bands with increasing vapor-density was studied, and some of the bands, notably λ 2768 and λ 3776, showed a marked asymmetry, broadening chiefly on the less refrangible side.

JOHNS HOPKINS UNIVERSITY
1908

ELEVEN STARS HAVING VARIABLE RADIAL VELOCITIES

By W. W. CAMPBELL

In the course of the regular observing programme with the Mills Spectrograph the following stars have been found to have variable radial velocities. The types of spectra are taken from the Harvard College Observatory *Annals*.

γ *Persei* ($\alpha = 2^h\ 57^m.6$; $\delta = +53^\circ\ 7'$)

Date	Velocity	Measured by
1897, January 19............	−0.9 km	Reese
1898, September 16.........	+0.5	Reese
1898, November 14..........	−1.1	Reese
1899, July 5................	−0.3	Reese
1901, December 4...........	−2.5	Reese
1904, October 25............	+5.5	Miss Hobe
1904, October 31............	+7	Moore
1904, November 23..........	+5	Moore
1906, September 19.........	+0.9	Moore
1908, October 31............	−0.7	Moore
1908, November 2...........	+0.1	Moore

The type of spectrum is G. This star is on the Harvard list of stars showing composite spectra. The variable velocity was detected by Mr. Moore. Its period is probably long.

ξ *Tauri* ($\alpha = 3^h\ 21^m.8$; $\delta = +9^\circ\ 23'$)

Date	Velocity	Measured by	
1903, November 24.............	−38 km	Campbell	λ 4481 only
	−39	Moore	4481
1903, December 7..............	+2	Curtis	4481
	+1	Moore	4481
1904, January 26...............	−59±	Campbell	4481 small weight
	−65±	Moore	4481 small weight
1904, October 18...............	+34	Campbell	4481
	+37	Moore	4481
1908, November 11.............	−4	Campbell	4481 and λ 4549
	−1	Moore	4481 only

The type of spectrum is A, with a very broad $H\eta$, and poor lines at λ 4481 and λ 4549. The appearance of λ 4481 seems to vary.

The variable velocity was detected by Mr. Campbell.

θ^2 *Tauri* ($\alpha = 4^h\ 22^m\!.9$; $\delta = +15°\ 39'$)

Date	Velocity	Measured by
1903, December 1	+39 km	Curtis
	+37	Moore
1905, January 3	+50±	Moore
1906, October 4	+74	Moore
1908, September 8	+80	Moore
1908, October 21	+17	Moore
1908, October 25	+23	Moore

The spectrum is of the A type. The lines λ 4481 and λ 4549 are broad but measurable. The variability was discovered by Mr. Moore. Its period is probably short.

l (53) *Eridani* ($\alpha = 4^h\ 33^m\!.6$; $\delta = -14°\ 30'$)

Date	Velocity	Measured by
1900, September 25	+36 km	Wright
	+34.1	Burns
1900, October 16	+35	Wright
	+33.1	Burns
1900, October 23	+35	Campbell
	+34.4	Burns
1904, December 6	+41	Moore
	+41.7	Newkirk
1907, October 30	+43	Moore
	+43.5	Miss Allen
1908, October 13	+42	Moore

This star's spectrum is type I. The variability was discovered by Mr. Moore. Its period is probably long.

ζ *Aurigae* ($\alpha = 4^h\ 55^m\!.5$; $\delta = +40°\ 56'$)

Date	Velocity	Measured by
1898, December 4	+4 km	Campbell
	+0.1	Burns
1899, December 3	+6	Campbell
	+5.0	Burns
1903, December 29	+3	Curtiss
	+2	Moore
1906, September 30	+3	Moore
	+3.4	Newkirk
1907, October 10	+4	Moore
1908, September 27	+25	Wright
1908, October 26	+20	Wright

This is one of the stars described by Miss Maury as having a composite spectrum.

The variation was detected by Mr. Wright on measuring the sixth plate.

ρ Orionis ($\alpha = 5^h\ 8^m.1$; $\delta = +2°\ 45'$)

Date	Velocity	Measured by
1902, October 14	+34 km	Curtiss
	+37.5	Burns
1905, September 25	+39	Moore
	+40.5	Newkirk
1906, September 17	+34	Moore
	+33.5	Newkirk
1907, November 7	+50	Moore
	+49.4	Miss Allen
1908, October 27	+36	Moore
	+35.0	Miss Hobe
1908, November 2	+33	Moore

The spectrum is type I. The variability was detected by Mr. Moore.

β Canis Majoris ($\alpha = 6^h\ 18^m.3$; $\delta = -17°\ 55'$)

Date	Velocity	Measured by	
1904, January 13	+39.8 km	Albrecht	Poor focus
February 1	+30.9	Curtiss	
1907, November 1	+39.9	Albrecht	
December 17	+28.3	Plummer	
1908, January 11	+28.2	Albrecht	
February 24	+33.0	Albrecht	
September 11	+31.9	Albrecht	
October 5	+40.2	Albrecht	
October 9	+40.0	Albrecht	
October 13	+37.4	Albrecht	
October 26	+35	Albrecht	
November 6	+36.5	Albrecht	
November 10	+27.0	Albrecht	
November 19	+40.9	Albrecht	
November 28	+28.7	Albrecht	
November 29	+27.0	Albrecht	
December 5	+34.1	Albrecht	

The type of spectrum is B. The variation was discovered by Mr. Albrecht. The period is short.

ν Draconis ($\alpha=17^h\ 30^m.3$; $\delta=+55°\ 15'$)

Date	Velocity	Measured by
1902, June 22	−13.6 km	Burns, Underexposed
1908, August 6	− 4.0	Albrecht, Underexposed
August 31	−23.2	Albrecht, Underexposed
November 2	−21.1	Albrecht
November 17	{ −21.5	Albrecht
	{ −21.4	Miss Allen

The type of spectrum is *A*. The variability was detected by Mr. Albrecht.

70 Ophiuchi ($\alpha=18^h\ 0^m.4$; $\delta=+2°\ 32'$)

G. M. T. of Observation	Observed Radial Velocities	Plate Measured by	G. M. T. of Observation 1895.00+	Observed Radial Velocities	Computed Radial Velocities
1897, May 11.95	−10.68 km	Burns	2ʸ.360	−10.68 km	−10.73 km
1898, May 4.97	−10.18	Burns }	3.423	−10.00	−10.33
July 4.84	− 9.82	Burns }			
1901, April 21.99	− 9.26	Burns	6.330	− 9.26	− 9.10
1902, May 26.90	− 9.95	Burns	7.397	− 9.95	− 8.69
1905, June 27.88	− 7.66	Newkirk	10.486	− 7.66	− 7.78
1908, April 26.99	− 6.73	Plummer }			
April 26.99	− 7.62	Miss Allen }	13.447	− 7.20	− 7.21
July 30.80	− 7.21	Miss Allen }			

This is a well-known double star, with components of 4.5 and 6.0 magnitudes, and revolution period of 88 years. The spectrum of the bright component is of K type. Its radial velocities have been measured as in the first and second columns of the above table. Combining the two observations of 1898 into one mean result, and the two of 1908 similarly, and expressing the times in mean solar years following the beginning of the year of periastron passage in the system, we have the fourth and fifth columns. Assuming the parallax of the star to be 0″.24, the value of the angle of inclination in the visual orbit to be −38°.57,[1] the relative masses of the primary and secondary to be as 3 to 2, and the radial velocity of the center of mass of the system to be −7.4 km, the computed values[2] of the radial

[1] Lohse's Elements, III, has been used (*Publ. des Astroph. Obs. zu Potsdam*, **20**, 143, 1908).

[2] The method is described in *L. O. Bulletin*, **3**, 81, 1905. The velocity equation used is $v=+3^{k}.077-6^{k}.340\cos(v+w)$, v being the velocity of the secondary with reference to the primary.

velocities of the primary are as in the sixth column. The fair agreement of the observed and computed velocities may be held to prove that the angle of inclination of the orbit plane is negative; but a considerably longer arc of the ellipse must be described before the speed of the center of the mass can be determined accurately; and the speed of the secondary is needed for a computation of the value of the parallax.

111 Herculis ($\alpha = 18^h 42^m.6$; $\delta = +18° 4'$)

Date	Velocity	Measured by
1902, June 15	−63 km	Burns
	−64	Wright
1905, June 21	−36	Wright
1908, August 4	−54	Wright
1908, October 28	−45	Wright
1908, November 4	−43	Wright
1908, November 15	−26	Wright

This star has a spectrum approaching the *Orion* type, but contains some additional lines. The above observations, which are to be considered as approximate, depend upon measurements of but one line, λ 4481.

The variable speed was detected by Mr. Wright.

ϕ Cygni ($\alpha = 19^h 35^m.5$; $\delta = +29° 56'$)

Date	Velocity	Measured by
1907, August 29	−24 km	Moore
	−24 and +30 km	Moore
1908, July 13	+ 3	Plummer
July 24	+ 2	Moore
November 16	0	Moore

The spectrum is classified as type I in the *Draper Catalogue.* The velocity was suspected by Mr. Plummer to be variable from his measure of the second plate. On examining the first plate, recently, Mr. Campbell noticed that two sets of spectrum lines are visible in nearly equal prominence. This star is thus of the class of binaries in which the spectra of both components are recorded.

LICK OBSERVATORY
December 1908

FIVE STARS HAVING VARIABLE RADIAL VELOCITIES

By HEBER D. CURTIS

The following stars have recently been shown to be spectroscopically double, in the course of the work of the D. O. Mills Expedition to the Southern Hemisphere.

ζ Canis Majoris ($\alpha = 6^h\ 16^m.5$; $\delta = -30°\ 2'$)

Date		Velocity	Measured by
1906	Nov. 7	+35 km	Paddock
		+31	Curtis
	Dec. 17	+38	Paddock
		+35	Curtis
1907	Oct. 4	+11	Paddock
		+12	Curtis
	Oct. 19	+19	Paddock
		+21	Curtis
	Oct. 30	+22	Paddock
	Nov. 7	+20	Paddock
	Nov. 8	+21	Paddock
	Nov. 12	+17	Paddock
	Nov. 23	+26	Paddock
		+25	Curtis
	Nov. 26	+29	Paddock
		+29	Curtis
	Dec. 2	+32	Paddock
	Dec. 4	+27	Paddock

This star is of type B3A and five lines of fair quality are available for measurement. The binary character of this star was discovered by Mr. Paddock from measures of the third plate. The period is probably long.

τ Puppis ($\alpha = 6^h\ 47^m.4$; $\delta = -50°\ 30'$)

Date		Velocity	Measured by
1903	Nov. 15	+39 km	Palmer
1904	Oct. 12	+34.4	Palmer
	Dec. 9	+33.0	Palmer
1905	Jan. 24	+33.1	Palmer
	Nov. 10	+34	Wright
1907	Jan. 15	+39.7	Curtis
	Jan. 19	+40.3	Curtis
	Oct. 4	+36.6	Curtis
	Oct. 13	+37.2	Curtis
	Nov. 23	+34.0	Curtis

This star is of type K with very good lines. The variable radial velocity was discovered by Mr. Curtis from definitive measures of the sixth plate and independently discovered by Mr. Palmer from measures made at Mount Hamilton of the first four plates taken. Though the variation is small, the character of the lines is such as to leave no doubt of its reality. The period is long.

o Velorum ($\alpha=8^h\ 37^m.4$; $\delta=-52°\ 34'$)

Date			Velocity	Measured by
1904	Feb.	4.657.........	+14 km	Palmer
			+14.3	Wright
	Nov.	15.833.........	+11.1	Albrecht
1905	Jan.	31.628.........	+10.0	Palmer
	Apr.	13.574.........	+11.0	Palmer
1906	Dec.	29.826.........	+16.0	Paddock
1907	Mar.	1.644.........	+19.8	Paddock
	Apr.	26.510.........	+19.4	Paddock
	Oct.	14.885.........	+18.6	Paddock
	Nov.	1.859.........	+17.4	Paddock
			+16.7	Curtis
1908	Jan.	13.770.........	+27.0	Curtis
	Feb.	10.636.........	+24.7	Curtis (II Prism)

This star is of type B3A; it has available six lines of *C*, *H*, *He*, and *Mg* of quite fair quality. The variation in the velocity was discovered by Mr. Curtis. The period is probably long.

d Carinae ($\alpha=8^h\ 38^m.5$; $\delta=-59°\ 24'$; Mag. = 4.4)

Date			Velocity	Measured by
1907	Nov.	7.............	+72 km	Paddock
	Nov.	14.............	+62	Paddock
	Nov.	23.............	+53	Curtis
	Nov.	25.............	+46	Curtis
	Nov.	26.............	+48	Curtis
	Dec.	2.............	+38	Curtis

This star is of type B2A and has available six lines due to *C*, *H*, *He*, and *Mg*, besides a few other lines too faint to use. The variation was discovered by Mr. Paddock from the measure of the second plate. The period is probably of some length.

q Velorum ($\alpha = 10^h\ 10^m.6$; $\delta = -41°\ 37'$; Mag. 4.0)

Date		Velocity	Measured by
1904	Apr. 10	− 1 km	Curtis
1907	Jan. 26	+25	Paddock
		+19	Curtis
	Apr. 30	− 2	Paddock
		− 1	Curtis
	Nov. 29	+21	Curtis

This star is of type A2F with very broad $H\gamma$ and two other broad lines; the measures are accordingly subject to considerable uncertainty. The variation was discovered by Mr. Paddock.

The D. O. Mills Expedition
Santiago, Chile
February 1908

TWO STARS HAVING VARIABLE RADIAL VELOCITIES

By W. H. WRIGHT

Spectrograms of the following two stars, secured by the D. O. Mills Expedition to the Southern Hemisphere, show their radial velocities to be variable:

ν *Puppis* ($\alpha = 6^h\ 34^m.7$; $\delta = -43^\circ\ 6'$)

The only line in the region covered by the plates is λ 4340.6 $H\gamma$. This presents the appearance of being made up of a fairly sharp line in the center of a broad absorption, suggesting that both components are bright. The central nucleus is easily measurable and very fair velocity determinations can be made from the single line. Variability was suspected from the fifth plate. The last three plates, kindly secured by Dr. Curtis, confirm this variation.

Date			Velocity	Measured by
1904	January	1	+33.0 km	Wright
	October	17	+33.7	Wright
	December	31	+34.9	Wright
1905	January	18	+33.4	Wright
	December	13	+28.2	Wright
1907	January	22	+29	Curtis
			+29	Paddock
1908	January	6	+20	Curtis
	January	14	+20	Curtis

ν *Octantis* ($\alpha = 21^h\ 30^m.4$; $\delta = -77^\circ\ 50'$)

This star has a spectrum of the solar type.

Date			Velocity	Measured by
1904	June	8	+29.0 km	Palmer
	October	13	+29	Palmer
			+28.5	Wright
1905	August	7	+39	Wright
			+36.5	Palmer
	September	6	+36.2	Wright
1906	October	31	+33	Paddock
1907	May	6	+30	Curtis
	June	22	+27	Paddock
	September	19	+32	Curtis

The variation was detected on measuring the third plate. The last four plates, which are fully confirmatory, were taken under the direction of Dr. Curtis.

Mt. Hamilton
October 6, 1908

SPECTROGRAPHIC NOTES

By EDWIN B. FROST

I. REANNEALED PRISMS

Those who have had to use large prisms in their spectroscopes are aware of the difficulty often experienced in obtaining glass of adequate homogeneity for refined work. This obstacle was encountered in the construction of the Bruce spectrograph, as recorded in this *Journal* (**15**, 14–15, 1902). The prisms were 57 mm high, of 66° angle, with faces of 117, 127, and 135 mm; for λ 4405, $n = 1.6374$. Having heard of the occasional success of reannealing, I took up the question with Mr. Brashear, who learned that the maker of the glass, M. Parra-Mantois, would be glad to undertake to reanneal the prisms which had proved so disappointing.

The process was completed and the prisms were returned from Paris to Pittsburg last spring. An examination of one prism which was at once figured by the Brashear Company indicated that the improvement was enough to justify putting new faces on all of the prisms, which was done. The prisms were now cut down somewhat, so that all three are of nearly the same dimensions: 54 mm high and 115 mm long in face.

A number of trial spectrograms of spark spectra and of sunlight were obtained with these prisms in the Bruce spectrograph, chiefly by Dr. D. V. Guthrie, who was spending the summer quarter here. The outcome of the trials was that although greatly improved, the three prisms together did not equal in definition the performance of the train of prisms of Jena flint O 102 regularly used with the instrument. The prism which was most cut down before it was figured, however, gave as fine definition as any one of the Jena prisms, and it was accordingly used for one-prism work with the spectrograph during a part of the summer, over 100 stellar spectrograms being obtained with it. The inconvenience of having the scale of the plates slightly different from that of the 1600 other spectrograms taken with one prism led to the subsequent restoration of the Jena prism to its position. The inference may be drawn by spectroscopists, however, that prisms lacking in homogeneity may in some cases be successfully reannealed, with great improvement in their optical performance. I am glad to put on record our appreciation of the interest and assistance of the Brashear Company in this experiment and of the generosity of M. Parra-Mantois in doing the work of reannealing without expense to the observatory.

II. PECULIAR SPECTROSCOPIC BINARIES

A peculiar interest attaches to those stars of the *Orion* type in which the characteristic lines are broad and diffuse but the H and K lines of calcium are narrow and sharp. Examples of such stars for which data have been published are *δ Orionis* and *9 Camelopardalis*. In his investigation of the spectroscopic orbit of the former, Hartmann reached the conclusion "that the calcium line at λ 3934 does not share in the periodic displacements of the lines caused by the orbital motion of the star."[1] In measuring the Bruce spectrograms of *9 Camelopardalis*, it was found[2] by Mr. Adams and myself that the H and K lines were very sharp and well suited for measurement and that they yielded a variable radial velocity differing from that given by the broad lines usually measured and from which the binary character of the star was first inferred. The detection of some peculiarities in other stars having such spectra led me about two years ago to examine all our spectrograms which included H and K. I was not prepared to find that such spectra were so common, for I was able to list about twenty-five stars having this spectrum. I was struck by the fact that about half of them had already been detected here as binaries from the variable displacements of the broad lines. For nearly all of the others, the data at hand were far too meager for definite inferences on this point.

This would accordingly seem to indicate that we are dealing in such cases with composite spectra. The general principle of such a discrimination was laid down long ago by Professor E. C. Pickering,[3] and it has been applied in the *Harvard Annals*, **28** and **56**, by Miss Maury and by Miss Cannon. This particular variety of composite spectrum has, however, not been described by the Harvard observers.

As the discovery of spectroscopic binaries here is incidental to our regular programmes, we have not yet been able to follow up the stars

[1] *Astrophysical Journal*, **19**, 273, 1904. [2] *Ibid.*, **19**, 350, 1904.

[3] "The Discovery of Double Stars by Means of Their Spectra," *Astronomische Nachrichten*, **127**, 155, 1891.

of this sort on our lists and find what precentage of those having sharp H and K, with the other lines broad, are *not* spectroscopic binaries.

When I noted recently the presence of sharp K in ϵ *Orionis*, I arranged to have a few spectrograms taken, in the confident expectation that variable velocity would be indicated, although the earlier observations by myself and Mr. Adams (with three prisms, spectrum measurable between λ 4340 and λ 4713) did not show variation. Mr. Lee has measured all of our one-prism plates with the following results:

RADIAL VELOCITY OF ϵ *Orionis*

Plate	Date	G. M. T.	Taken by*	Broad Lines		H and K		Quality of Plate†
				No.	Velocity	No.	Velocity	
					km		km	
IB 227	1903 Dec. 26	17h 20m	F.	6	+30	..	....	..
484	1905 Jan. 21	15 49	F.	6	22	..	....	g.
1327	1908 Jan. 14	15 55	B.	5	27	2	+31	g.
1337	Jan. 17	18 10	L.	5	30	2	41	g.
1353	Jan. 20	15 1	B.	6	28	2	23	w.
1463	Feb. 17	13 39	P.	6	17	2	20	g. w.
1496	Feb. 21	13 19	F.	8	30	1	39	g.
1770	Oct. 2	23 1	L.	7	35	2	23	v. g.
1788	Oct. 9	23 3	L.	6	30	..	....	g } too weak for *Ca* lines
1805	Oct. 16	23 15	L.	8	27	..	....	v.g
1813	Oct. 30	23 53	L.	8	30	2	28	p.
1905	Dec. 14	21 0	B.	6	37	2	28	g.
1926	Dec. 26	15 30	F.	8	30	2	30	v.g.
1946	1909 Jan. 1	18 0	B.	8	16	2	20	v.g.

* B.=Barrett; F.=Frost; L.=Lee; P.=Parkhurst. Mr. Sullivan assisted as usual in guiding.
† g=good; p=poor; w=weak.

The earlier measures[1] of three-prism plates are added for completeness:

Plate	Date	G. M. T.	No.	Adams	No.	Frost
A 208	1901 Sept. 4	22h 10m	3	+28 km	..	......
B 228	Nov. 13	19 50	6	29	5	+24 km
B 298	1902 Mar. 13	15 11	5	26	4	26
B 316	April 9	14 21	3	26	3	28

[1] "Radial Velocities of Twenty Stars Having Spectra of the *Orion* Type," *Publications of Yerkes Observatory*, **2**, 210, 1903.

The inference is that in this case the H and K lines share in the oscillations of the broad lines, so that this would not be an instance of a composite spectrum.

I reserve for a later discussion the remarkable feature of the binary character of some of these stars, already alluded to, that the component responsible for the sharp H and K lines appears to have a different velocity (γ) of its orbital center of gravity from that of the component having broad lines. The first inference in such a case would be that we are dealing with a quaternary system—two pairs of spectroscopic binaries; if so, however, a change in the relative velocity of the center of gravity would be expected within a few months or years, and in at least one instance our observations cover a longer period of time.

I have in mind particularly the star *ξ Persei*, the first observations of which were made by Mr. Adams[1] in 1903. The five plates then measured yielded a velocity of +85 km, which would be entirely exceptional for a star of the *Orion* type not a spectroscopic binary. We therefore expressed the opinion that later observations might be expected to show the star to be a binary. A range of 30 km was given by a plate taken later in that year, establishing the variation in velocity, and we have been observing the star occasionally each year since, so that we now have over 30 spectrograms, of which about one-half are measured. We do not appear to have caught the star with a negative velocity on any plate, the total range shown on our measured plates being about 60 km. Mr. Plaskett reports his measures of 7 plates taken in the autumn of 1908 in the *Journal of the R. A. S. of Canada* (**2**, 325, 1908), giving a range of velocity from −2 to +143 km.

The lines are exceptionally broad and diffuse, even for spectra of that type, but H and K are quite sharp, although H cannot always be separated from *Hε*. In 1906 at my request Mr. Ichinohe measured the ultra-violet portion of a number of the earlier plates, and obtained for the calcium lines only moderately positive velocities, having a range of about 25 km, but differing greatly from the values derived from the broad lines (generally by not less than 50 km). I have also measured some later plates with similar results. The star evidently is of the sort of *9 Camelopardalis* and *δ Orionis*, but

[1] *Astrophysical Journal*, **18**, 388, 1903.

its thorough investigation will be a difficult task on account of the evil character of the broad lines.

I am well aware that Professor Julius finds an explanation of such stars in anomalous dispersion, regarding the broad lines as dispersion bands.[1] Perhaps some physical effects will have to be invoked to explain the peculiarities of such stars; but I am not yet convinced that anomalous dispersion is here a sufficient cause.

III. SPECTROSCOPIC BINARIES AMONG STARS IN PROFESSOR BOSS'S STREAM IN *TAURUS*

In a brief paper read at the Baltimore meeting of the American Association I reported on the beginning made here in observing the radial velocities of the stars in the "moving cluster in *Taurus*" described by Professor Lewis Boss in No. 604 (**26**, 31, 1908) of the *Astronomical Journal*. As my remarks were printed in *Science* (**29**, 156, 1899), practically in full, I will not repeat myself further than to state that observations of those 40 stars have now been in progress, as circumstances permitted, for about six months with the Bruce spectrograph, a dispersion of one prism, which is as high as many of the spectra will stand, being employed.

About seventy spectrograms have been so far obtained, chiefly by Mr. Barrett and Mr. Lee, of 21 of the stars. The six stars of that list which we had found to be spectroscopic binaries at the time that paper was prepared, were: *90 Tauri* and *B. D.* 15° 637 found by Mr. Barrett; *64* and *97 Tauri*, found by Mr. Lee; and θ^2 and v *69 Tauri*, found by myself. Two that I then regarded as suspicious, *71 Tauri* and *92 Tauri*, have since proved by measurement to be also variable in velocity. The particulars of the measures thus far made of six of these stars will be given here and in the following note by Mr. Lee. Mr. Barrett will report later on his measures of *90 Tauri* and *B. D.* 15° 637. It must be acknowledged that the proportion of binaries is surprisingly large, 8 out of the 14 stars for which we have two or more spectrograms.

The observations with the Bruce spectrograph indicate a proportion of spectroscopic binaries of not less than 1:3 among stars

[1] "Dispersion Bands in the Spectra of δ *Orionis* and *Nova Persei*," *Astrophysical Journal*, **21**, 286, 1905.

of the *Orion* type, but the proportion here would seem to be still greater. The 14 stars, with one exception, have spectra of the first type or of one intermediate between the first type and the early solar type: in the current Harvard designation they are of types A, A2, A3, or A5, with the exception of θ' *Tauri*, of type K.

The spectrum of θ^2 *Tauri* is of type A5. With a dispersion of two prisms (scale at λ 4500 : 1 mm = 15 t.-m.) the lines are very diffuse for measurement; with one prism the lines are better, but some seem to be complicated by the presence of companions due to a second component. The radial velocity is therefore liable to considerable uncertainty. On being informed by Professor Boss regarding his cluster, I asked Mr. Lee to measure the two plates of this star then on hand, both taken with two prisms. The other measures are by myself. The variable radial velocity was at once apparent after we began to get spectrograms with one prism.

θ^2 *Tauri* ($\alpha = 4^h\ 23^m$; $\delta = +15°\ 39'$; Mag. = 3.7)

Plate	Date	G. M. T.	Taken by	No. Lines	Velocity	Remarks
IIB 86	1906 Aug. 31	$21^h\ 11^m$	F.	4	+42 km	
180	1907 Nov. 4	18 32	L.	4	(+29)	Very weak
IB 1707	1908 Aug. 25	22 32	B.	5	+64	
1734	Sept. 8	22 45	B.	6	+88	
				2	+40	Second Component
1741	Sept. 18	20 32	L.	7	+10	
1794	Oct. 12	20 25	B.	4	+39	
				3	+ 8	Second Component
1836	Nov. 8	18 46	L.	5	+36	
1895	Dec. 7	15 1	L.	5	+38	
1900	Dec. 11	15 2	F.	4	+31	

The spectrum of *69 Tauri* is a very difficult one to deal with. To classify it as of type A5 fails to express the diffuse character of the lines. My re-examination of our first plate, taken three years ago, led me to believe that the spectrum is composite and this was confirmed by the measures of the subsequent plates. It is difficult and often incorrect to combine into means the velocities from lines which in some cases belong to different components; where the components are not separated, the setting on the center of the apparently single line has no definite meaning. My measures are as follows:

69 (Upsilon) *Tauri* ($\alpha = 4^h\ 20^m$; $\delta = +22°\ 35'$; Mag. = 4.5)

Plate	Date	G. M. T.	Taken by	No. Lines	Velocity
IIB 24	1905 Nov. 24	$17^h\ 26^m$	B.	{ 2 2	− 81 km + 16
IB 1747	1908 Sept. 21	19 40	B.	2	+102
1896	Dec. 7	16 21	L.	{ 1 2	+ 82 +130
1901	Dec. 11	16 1	F.	6	+ 38
1954	1909 Jan. 3	18 28	B.	2	+ 34

YERKES OBSERVATORY
February 17, 1909

VARIABLE RADIAL VELOCITIES OF FOUR STARS IN THE *TAURUS* STREAM

By OLIVER J. LEE

The following measures have been made on Bruce spectrograms taken with one prism. They were reduced with the aid of tables constructed in the manner employed by Professor Schlesinger.[1]

64 Tauri ($\alpha = 4^h\ 18^m$; $\delta = +17°\ 13'$; Mag. = 5.1)

Plate	Date	G. M. T.	Taken by	No. Lines	Velocity	Quality
					km	
IB 1786	1908 Oct. 9	$20^h\ 47^m$	L.	15	+32	v.g.
1848	Nov. 10	19 29	L.	13	+44	v.g.
1856	Nov. 13	19 18	L.	12	+38	v.g.
1864	Nov. 16	16 24	L.	12	+33	v.g.
1886	Dec. 4	19 51	L.	13	+44	v.g.

The spectrum of the star *64 Tauri* is of type A2 in the notation of the *Revised Harvard Photometry*, or Vogel's Ia2. The lines are numerous and well defined, so that there can be no doubt of the binary character of the star, although the range thus far observed, 12 km, is rather small. A period of 12 days is suggested by the observations thus far, but later plates may indicate a sub-multiple of this period. A higher dispersion could be used to advantage with this star, and spectrograms will be obtained with two prisms.

The three other stars have complex spectra, and it was the double appearance of some of the lines on the first spectrograms obtained that rendered the stars suspicious. It was necessary to make settings upon what seemed to be the separate components, a difficult procedure in many cases. Where the lines appeared single the settings were made upon the centers, but this may introduce error where the lines were actually double but too confused for separate recognition. It will thus be understood that the values given for centers are not

[1] *Publications Allegheny Observatory*, **1**, 9, 1908.

averages of the settings on the component. The measures on the centers show a velocity variable by as much as 30 km for each of the stars, probably chiefly due to unequal light-effect of the two components, and partly to lines present in only one component.

97 i Tauri ($\alpha = 4^h\ 45^m$; $\delta = 18°\ 40'$; Mag. = 5.3)

Plate	Date	G. M. T.	Taken by	Center		Violet Comp.		Red Comp.		Quality
				No.	Vel.	No.	Vel.	No.	Vel.	
					km		km		km	
IB 1787	1908 Oct. 9	$22^h\ 8^m$	L.	4	+41	3	−14	1	+ 88	v.g.
1832	Nov. 6	22 9	L.	4	+53	..	...	..	...	g.
1907	Dec. 19	17 3	L.	7	+19	2	−52	3	+ 90	g.
1912	Dec. 21	17 3	L.	3	+28	5	−11	2	+103	g.

This spectrum is classified as A5, but the lines are so diffuse and complicated that accuracy of measurement is not possible. In many cases normally simple lines are split up into two or three parts. On one plate only, No. 1832, do the lines seem relatively simple.

71 Tauri ($\alpha = 4^h\ 21^m$; $\delta = +15°\ 24$; Mag. = 4.8)

Plate	Date	G. M. T.	Taken by	Center		Violet Comp.		Red Comp.		Quality
				No.	Vel.	No.	Vel.	No.	Vel.	
					km		km		km	
IB 1748	1908 Sept. 21	$20^h\ 47^m$	B.	6	+12	4	−61	6	+44	v.g.
1902	Dec. 11	17 17	F.	8	+ 9	2	−18	2	+57	v.g.
1910	Dec. 21	14 37	F. L.	10	−21	..	....	..	....	v.g.
1962	1909 Jan. 25	13 48	F. L.	6	− 9	4	−97	..	....	p.
1972	Feb. 1	12 2	L. B.	4	+18	7	−90	2	+82	v.g.

The spectra of this star and the next are classed as simply A in the *Revised Harvard Photometry*, but there is some difference in the accuracy of measurement possible. In *71* the lines are diffuse, with confusing indications of a second component on three of the plates. On plate No. 1910 there was no indication of the presence of a second component. The centers were measured as in the case of *97 Tauri*. The results are liable to considerable uncertainty.

92 σ^2 Tauri ($\alpha=4^h\ 34^m$; $\delta=+15°\ 43°$; Mag. = 4.5)

Plate	Date	G. M. T.	Taken by	Center		Violet Comp.		Red Comp.		Quality
				No.	Vel.	No.	Vel.	No.	Vel.	
					km		km		km	
IB 1804	1908 Oct. 16	$22^h\ 10^m$	L.	7	+42	6	0	3	+ 97	g.
1838	Nov. 8	21 20	L.	6	+27	5	−26	6	+ 71	v.g.
1944	1909 Jan. 1	15 18	B.	6	+ 2	3	−67	7	+ 46	g.
1952	Jan. 3	13 44	B.	7	+17	7	−42	8	+ 79	v.g.
1963	Jan. 25	14 37	L.	8	+18	2	−88	2	+102	p.
1973	Feb. 1	12 56	B. L.	11	+31	..	....		....	g.

In this star the double character of the lines is quite evident, and measurements of the separate components are certainly more accurate than in the case of *71*. Only one plate, No. 1973, gives simple lines.

Yerkes Observatory
February 17, 1909

SERIES IN THE BARIUM SPECTRUM

By W. RITZ

The previously unknown triplet series of barium has recently[1] been discovered and published by F. A. Saunders. Very few terms of the series were observed, and since these were not represented by formulae known to be applicable to *Mg*, *Ca*, and *Sr*, the choice of lines may seem at first to be somewhat doubtful. The following remarks will, I think, serve partly to verify his results.

The lines of the first subordinate series may be accurately represented by either of the two following formulae:

$$\nu = A - \frac{109675.0}{\left[m + a + \frac{b}{m^2}\right]^2} \qquad (1)$$

$$\nu = A - \frac{109675.0}{[m + \alpha + \beta 10^{-5}(A - \nu)]^2} \qquad (2)$$

which, as I have shown,[2] serve to represent with great accuracy the series of other elements. In these formulae A, a, b, α, and β are constants; m a whole number, and ν the wave-number (per cm) in vacuum.

For the strongest (and most completely observed) lines we obtain, for instance:

m=	3	4	5	6	7
λ obs.	5777.84	4489.50	4084.94	3895.2	3787
ν obs.	17302.8	22268.1	24473.4	25665.4	26399
Error (in Å.)	0.00	0.00	+0.02	+0.6	−0.5

The differences are throughout smaller than the errors of observation. In this case $A = 28472$; $a = +0.29581$; $b = -1.4600$. In the corresponding cases for *Mg*, *Ca*, *Sr*, the constant $a+1$ has the values 0.842, 1.090, and 1.222; the value for *Ba*, 1.296, fits in well with these. The alkalies furnish a progression which is very similar.

The wave-number difference $\nu = 878.0$, divided by the square of the atomic weight (μ) gives $47.0 \cdot 10^{-3}$, while the values for *Mg*, *Ca*, and *Sr* are $68.8 \cdot 10^{-3}$, $66.1 \cdot 10^{-3}$, and $51.5 \cdot 10^{-3}$. As I have pointed

[1] *Astrophysical Journal*, **28**, 223, 1908.

[2] *Annalen der Physik*, **12**, 264, 1903.

out,[1] the quotient $\frac{p_1-p_2}{\mu^2}$, calculated from the limits of the series, varies still less from element to element,

$$\frac{(p_1-p_2)10^5}{\mu^2}=0.146(Mg)\ ;\ 0.177(Ca);\ \ 0.157(Sr)\ ;\ \ 0.148\,(Ba)\ .$$

Finally, the separations of the satellites of the strongest lines of the first members ($n=3$) vary approximately as the square of the atomic weights. This requirement is also fulfilled in this case. From these facts it is evident that the first subordinate series of *Ba* is correctly given by Saunders.

The same conclusions hold for the first two triplets of the second subordinate series. Since the quotient $\frac{\beta}{a+0.5}$ varies but little among the members of a group of chemically related elements, I have already[2] given a probable value of 0.825 for this number in the case of *Ba*. Granting that the limits of the two series are the same, we have left in the equation of the second subordinate series only a single constant, a, to be calculated. In the red and ultra-red, where the first term of the series must lie, only one triplet was found with the proper separations. If we use this to calculate a, the formula so derived leads to the second triplet given by Saunders to within 5 Å., and this is a very small error when we consider that both the number 0.825 and the limit of the first subordinate series[3] are very uncertain. Thus both these triplets doubtless belong to the second subordinate series. If we now determine A and a from these two triplets, we find $\lambda=4248.4$ for the strongest line of the third triplet, while Saunders gives 4239.91. The use of the formula therefore leads us to doubt the propriety of classifying this triplet (and those following) in the series. It is possible, as Saunders remarks, that the formula does not fit this series, notwithstanding the fact that it successfully represents the second subordinate series of all the elements; but further investigation of the missing lines of the triplets of this series must be made before the question can be definitely settled.

GÖTTINGEN
January 1909

[1] *Astrophysical Journal*, **28**, 237, 1908; *Physikalische Zeitschrift*, **9**, 521, 1908.

[2] *Annalen der Physik*, **12**, 309, 1908.

[3] The formulae (1) and (2) represent, in general, the first subordinate series (especially of *Ca*) less exactly than the second; if only a few terms are known, and these only inaccurately, considerable errors in A may result.

REVIEWS

The Study of Stellar Evolution: An Account of Some Recent Methods of Astrophysical Research. By GEORGE ELLERY HALE. Chicago: The University of Chicago Press, 1908. Pp. xi + 252; with 104 plates. $4.00 net.

Hale's book on the *Study of Stellar Evolution* will be welcomed with the keenest pleasure and interest by a host of readers and students of astrophysics. The book was first planned to serve as a handbook for the use of the numerous visitors to the Yerkes Observatory; but when Professor Hale went to organize the new Solar Observatory of the Carnegie Institution, now splendidly established on Mount Wilson, in California, he decided to enlarge the scope of the book and make it a handbook for the use of visitors to both of the named observatories. By describing a connected series of investigations in stellar evolution, Professor Hale makes the opportunity of indicating from personal experience the observational methods adopted at both places. The result is an intensely interesting narrative from the pen of a pioneer who is in the thick of his adventurous work. It discloses to minds that are not conversant with the aims of the investigations of practical astronomers something of the hopes, difficulties, and achievements that go to make up the zest of life for one who is successfully engaged in developing a new attack on a problem, that has in large measure defied the efforts of the last forty years. To such minds it will perhaps convey the idea that the whole matter is to be settled by this onslaught; for Hale writes with that deep conviction that serves as motive power to an intrepid investigator, and he has set forth the subject with such consistent simplicity that the lay mind is sure to feel that, after this work is completed, there will be little left for astrophysicists to do.

Hale's narrative brings interest to very varied minds, and consequently lends itself to review from many points of view. The most difficult part of the task of the reviewer is to decide which point of view he is to take. I propose to resist the temptation to be purely descriptive, preferring rather to let myself be caught by the spirit of the pioneer and to join Hale, however inadequately, in looking out over the country to be explored. My point is that students of astrophysics as well as eager visitors to the large observatories owe a debt to Professor Hale for having devoted much of his time to writing this handbook. And how can a reviewer, who is interested in the subject that has been helped by Hale's book, show his appreciation better than by trying to put down thoughts that have been stimulated by the perusal of the book?

Any attempt, such as Hale makes, to lay before a wide audience a consistent representation of a subject like astrophysics must needs start from some more or less generally accepted standpoint. Hale carefully sets forth what may be called the case for temperature variation, and he uses it freely in summarizing the varied phenomena of stellar and solar spectra. A reviewer would be doing poor service if he were to seem to pin an author to statements in a handbook as if they were parts of his final creed. He must rather feel that he has, as it were, joined a field excursion and has been hearing a pioneer sketch out to a crowd of varied minds the lie of the country. According to the amount of study he has devoted to the subject the student will recognize the importance which the pioneer attaches to some of those dim ranges in the landscape, to which he has only passingly referred. His thoughts will go wandering on; the definite words to which he has been listening, used for stating an accepted view, may only tend to fix in his mind a diametrically opposite view. And if I use the opportunity afforded by this review to give utterance to thoughts that have long occupied my mind, I am sure I shall not be understood as offering cheap criticism of an admirably fair-minded and stimulating exposition of the present situation in an important part of astrophysics. I wish rather to plead for the consideration of a new aspect of the whole subject. Tersely put, the new aspect to be considered is: can it be that the main characteristic spectroscopic phenomena of the sun and the stars are dictated mainly by matter brought from without, and not mainly by matter brought from within the body of the sun and the star?

First let me quote a few lines from a notice written by myself in the *Observatory* (October 1908, p. 378):

Realize how the search is baffled whether on the purely physical side of the interpretation of general spectroscopic phenomena or the astrophysical applications. The statement of the problems today—as given, for instance, in chaps. ix, x, xi, xvii, xviii, xx—is nearly the same as the statement forty years ago. It seems as if the methods of analysis and discussion of isolated phenomena on physico-mathematical lines had proved too refined to cope with the broad aspects of the involved conditions of the questions to be elucidated. There were no signs of an immediate development of a more embracing method of solution on these lines.

But now comes Hale's method of the spectroheliograph, which automatically co-ordinates in a single record the many discordant isolated observations of the earlier days, and even those of today. Strange to say, it is as if the sight of the aggot is likely to help us to break the single sticks, an inversion of *divide et impera*.

Such an achievement leads us to hope that the work is to land us, if it has not already landed us, on a new platform, where the horizon and extent of the subject is so much enlarged that the mind finds itself again. The way is opened afresh for the physico-mathematical attack on broader lines.

As an instance of the baffled search, let us consider the case of widened lines in the spectra of vapors. Such widening is generally attributed to pressure, and Rayleigh and Michelson have indicated the paths along which explanation of the effect may be sought by calculating (1) the magnitude of the Doppler effect arising from the velocities of the light-giving atoms or molecules; and (2) the amount of the ill definition of lines arising from the shortness of sequences of undisturbed undulations (limitation of free path). These results show good agreement between theory and observation for the narrower lines in spectra. Michelson's expression for widening produced by shortness of sequences (limitation of free path) is of the form

$$\delta_2 = \frac{\lambda^2}{\rho} \frac{v}{V},$$

where δ_2 is the widening, ρ the free path, v the temperature-velocity of the molecules, and V the velocity of light. Thus when ρ is of the order of magnitude of the wave-length λ (and this is the case for pressures of the order of 100 mm of mercury for hydrogen), the widening by limitation of free path is of the same order of magnitude as the widening from the Doppler effect.

But there appears to be a source of widening which evades this analysis unless we are willing to admit a limitation of free path far more stringent than that imposed by the ordinary molecular kinetic theory. To take a single case, the experiment of passing electric sparks through unignited coal-gas in the absence of air shows that exceedingly wide lines may be produced at atmospheric pressure. The experiment is performed by putting sparkling terminals inside a glass tube, the ends of which are then connected by rubber tubing with a gas-main and with any convenient burner to get rid of the gas that passes through the tube. The spectrum of the sparks exhibits the hydrogen lines; and by manipulation of the spark-strength the hydrogen lines may be made either quite narrow or so broad as eventually to meet and so give a continuous spectrum. The widening is in the main symmetrical, a fact which would seem to rule out an explanation based on a change of molecular periods whether by loading or by increase of the forces under which molecular vibrations take place. Apart from a special and consequently unlikely combination of the two causes alluded to, an explanation lies in a new order of limitation of free paths, involving collisions or disturbances about a thousand or ten thousand times more frequent than those provided for in the ordinary kinetic theory.

Such an increase in the number of disturbances might fairly be ascribed to multitudes of corpuscles (J. J. Thomson) set free in the passage of the electric spark. But putting explanation aside, the experiment shows us that we are able to fix, at any rate momentarily, a mode of excitation of luminosity which gives exceedingly wide lines at low pressures; and it points to the existence of a peculiar condition, of which we have not yet complete control nor complete knowledge.

As another instance of baffled search, we find (1) that in the spectrum of almost every element under apparently any given conditions of pressure and temperature and electrical excitation some lines are broad, others narrow; and (2) that if any one of the conditions is varied, the relative width and brightness of the lines is in general changed. Thus in observations of the electrical arc under pressure (e. g., Duffield, *Phil. Trans.*, A, **208**, 157, 1908) it would appear that alteration of pressure under fixed electrical conditions may be accompanied by the same sort of changes in certain lines as are produced by a change of electrical excitation under fixed conditions of pressure. We are not yet in possession of a knowledge of the relation that must subsist between the variables defining the state of a gas, in order that a prescribed condition of luminosity may be evoked. All that we seem entitled to say is that we can in many cases evoke a prescribed state of a given line in a spectrum by proper adjustment of the conditions of excitation, pressure, and temperature.

I wish then to emphasize the statement that there is strong evidence that widening of lines may arise from a special mode of (electrical?) excitation even at low pressures.

Now widened lines, like those of hydrogen, helium, calcium, magnesium, etc., are a marked criterion in our accepted classification of stellar spectra. I would ask, do we not allow ourselves to adopt them without duly understanding their significance?

Let us look at the usual classification of the stars according to their spectra. We will make the authoritative statements in a type appropriate to the textbook, while the queries of an impetuous lay-reader shall be hushed in smaller type:

The usual classification begins with the blue stars; their spectra are marked by sparse and fine metallic lines together with broad hydrogen lines and sometimes broad helium lines; these are early stars with diffuse atmospheres.

Then, if breadth of line is a sign of pressure, does this mean that the hydrogen is under higher pressure than the metallic vapors in these early stars?

Perhaps, but let us proceed with the classification. The next class are the more condensed yellow stars of solar type.

Then, if the stars are more condensed, the lines are broader generally?

No, the lines are sharper; sharper hydrogen lines, and sharper metallic lines, except the calcium lines like H and K, which are strong and broad, forming a characteristic feature in stars of solar type.

Then the calcium is probably in the lower strata of the atmospheres of such stars?

Well, solar prominences point to its being outside in a rarified condition, and the spectroheliograph indicates that some rarified calcium is glowing brightly and irregularly over the surface of the sun, whilst the darker patches are possibly beneath and at much greater pressure.

Then, near the edge of the sun's disk the effect of the pressure will be more marked? I mean because the paths are relatively longer in the lower strata; are they not?

Yes, it is true that through three superposed strata, each of thickness 1000 kilometers, the paths of light near the sun's limb in the direction of the earth would be 120,000, 50,000, and 40,000 kilometers, if we neglect refraction.

Then, I suppose the widened edges of the K line are much darker at the edges of the sun's disk?

No. Hale's observations show that they are weaker, but then you have to take account of the filamentary structure of the photosphere. But we must return to the classification. The third class are still further condensed than solar stars. The characteristic features in their spectra are the marked bands which are believed to be due to titanium oxide and perhaps other compounds which only begin to be formed at temperatures lower than those at which *elements* (as opposed to compounds) are vaporized.

Then the compounds form first on the cooler outskirts of the star's atmosphere, I suppose? The metallic lines are of course much broader in this third class?

No, the metallic lines are still sharp.

Oh. And wait a moment, why don't the titanic oxide strata form outside the solar stars too? Such stars must get cooler in the upper strata of their atmospheres.

Yes, but it is a question of depth of strata as well as relative temperatures.

Then the bands might be visible at the limb of the sun?

Yes, they might be: but they are not visible there, at any rate not nearly so strongly as in sun-spots.

Oh, they are visible *locally* on the sun. Does not that point to special supplies of the proper material? Curious that the metallic lines are not widened! Are they widened in the fourth class?

The fourth class are marked by bands turned the opposite way to the titanium oxide bands; they are due to carbon compounds. The metallic lines are still narrow.

I advise you to look after those fine metallic lines. They don't look like high pressure.

We find the classification very convenient.

Doubtless a better presentment could easily be given of the position of both textbook and reader, but this is enough to serve my point: namely, to insist that in our attempt to justify a convenient empirical classification we seem unconsciously to reserve for ourselves the right to pick out of a multitude of criteria now one, now another, without ever consistently searching for binding relations between the criteria or rigorously following them out to their inevitable conclusions. We blind ourselves to the fact that laboratory phenomena clearly show that almost any element taken at random under chance conditions of luminosity will by its different lines afford examples of all the different affections of spectrum lines seen in a given star spectrum. We refuse to admit that it is the star which exercises eclectic choice, and commits itself in general to a fixed and constant type of spectrum—full of apparent inconsistencies.

Is a fixed and constant spectrum what we are entitled to expect of a star? I would say no. We realize from the comparison of a few of Hale's spectroheliograms how unwise it is to expect that suns, in which one of the essential factors in the mechanism of radiation is the *radial* convection currents, should show any spectroscopic symptoms of permanent tangential stratification. Consider this aspect of the case a little in detail.

I wish to bring forward three points, A, B, and C.

A. First, we will for a moment confine attention to the calcium (K_2) spectroheliograms. In such pictures we find that neighboring regions on the sun exhibit very different intensities of the incandescence of K_2 calcium. The dark regions are those where the incandescence of K_2 is feeble or where the motion in the line of sight is so great that the K_2 line is displaced off the second slit of the spectroheliograph. If we set aside this latter cause of dark flocculi on the ground that it is probably capable of producing only a small part of the observed darkening, we may take it that these spectroheliograms prove that calcium glows with very different intensities in different parts of the sun's surface.

If it should happen that the integrated area of the bright regions over the whole disk of the sun were greater than the integrated area of the dark regions, then the spectrum of integrated sunlight would exhibit a bright calcium line. Its easy detection as a bright line depends, however, on the existence of the dark wings of K_1; for if these wings did not exist, the bright K_2 line would appear as bright as the neighboring continuous spectrum, since it seems to be the observed fact that the bright K_2 line over a bright flocculus is about equal in intensity to those parts of the continuous spectrum which are not darkened by the wings of K_1. Thus but for the darks wings of K_1 the calcium line would appear as a narrow dark line over a dark flocculus; it would not appear at all over a bright flocculus. In the case of the sun, however, the dark wings of K_1 are always present. Hence (*a*) if the actual sun were observed as a remote star, at a time when the integrated bright flocculi were in excess, its stellar spectrum would exhibit a broad and dark K_1 line with a bright K_2 center; whereas if the integrated bright flocculi were in defect, the bright center would not be visible. And (*b*) if we had to do with a sun, whose spectrum did not exhibit dark wings of K_1, then the stellar spectrum would show a dark K_2 in times of defect of bright flocculi, whereas in times of excess the line would be simply obliterated.

These considerations (relating, it is true, to a single line) are enough to show in what marked degree a stellar spectrum may be a *residual* phenomenon in the conflict of two opposed conditions, represented by dark flocculi and bright flocculi. (The bright calcium flocculi are most noticeable in the obviously disturbed regions of sun-spots. They call for special consideration in a later paragraph.) Apart from the sun-spot zones, the calcium flocculi are distributed in a mottled structure over the whole disk of the sun in a way that suggests the active influence of radial convection currents, which seem to reach almost the upper surface of the reversing layer. But the persistence of the darkness of the K line in the *integrated* solar spectrum shows that in this general mottled network of flocculi the dark regions are greatly in excess of the bright flocculi; there is in fact in ordinary solar conditions no risk of that degree of variability in the K line, that would make it bright at one time and dark at another. In other words, the stability of the condition that gives a dark K line is considerable and is not likely to be upset by the convection currents beneath the reversing layer. It is otherwise evident from a comparison of the numbers of stars of different special types that the solar spectrum is in a sense an indication of a condition of fairly stable equilibrium of some sort.

With respect to the radial convection currents let me call to mind how

Kelvin's estimate of the power of sunlight per square meter of sun's surface has been put by Schuster in the following form:

> Taking the pressure of the vapor near the surface to be one atmosphere, we may say that all the heat contained in a layer having a thickness of 370 meters is lost by radiation in each second of time, and this number does not depend on the nature of the vapor or on its temperature. A layer of that thickness would have to be replaced by convection in every second if the temperature of the surface is to be maintained.—(*Astrophysical Journal*, **17**, 173, 1900.)

I would therefore put it that though these powerful radial convection currents form a mechanism which is well fitted for maintaining a photosphere, they are hardly suited for producing a permanent spectrum ascribed to vapors floating over it. Hale's spectroheliograms in fact seem to afford proof that the reversing layer is one of considerable thickness. The brightest flocculi, however, in the disturbed regions near sun-spots appear at first sight to demand mechanism of a different kind. But I incline to believe that one general scheme subject to local differences can be imagined which will serve to co-ordinate most of the phenomena of stellar and solar spectra.

I find myself provisionally regarding all stellar spectra and also local spectroscopic phenomena on the sun as conditioned, not mainly by matter which comes from within the body of the sun or star, but by matter which comes from without and is more or less slowly working in upon the photosphere.

Schwarzschild's idea of radiative equilibrium (*Nachrichten d. K. Ges. d. Wiss.*, Göttingen, 1906) is very helpful in this view, but, as I understand it, he is inclined to regard it as applicable to the case of what one may describe as a finished sun radiating in empty space.

My view would rather be that we must never lose sight of the constant activity of the gravitational attraction of the sun. Matter is always coming in, sometimes in the shape of meteoric stones and rocks, sometimes in finer dust or vapor. The rapid approach of cold dust to a raging sun and the rapid recession of hot dust from it will inevitably result in splintering and splitting. Radiation pressure will exert a sifting action, and thus the most finely divided matter—much in molecular state and the rest nearly so—will be that which will "settle" in superbly equably mixed state upon the sun after circulating round it for perhaps months. Leaving on one side for the moment the consideration of the question of organized rotation in the reversing layer, the mechanism which I suggest seems to be more in conformity with our knowledge of what goes on in the solar system; and so far as I have been able to test it, it seems to be a more resourceful aspect of the phenomena of stellar spectroscopy.

B. The second point is as follows. Hale's success in taking hydrogen spectroheliograms has led him to the discovery of the remarkable fact that in general where calcium flocculi are bright there are dark hydrogen flocculi. The discovery is, not only that hydrogen flocculi are distributed over the sun's surface irregularly, bright here and dark there, but also that the distribution of the hydrogen flocculi is complementary in a sense to that of the calcium flocculi. Now this would seem to indicate that the seat of the flocculi is the same, and that there is not a difference in level between the strata in which the calcium and hydrogen flocculi appear, but that the excess of incandescence of hydrogen is connected in some way with the defect of incandescence of the calcium. Were the observed fact to be referred to changed conditions *in different levels*, it would appear that the only way of accounting for the complementary nature of the phenomena would be to admit one of three views: (1) that the incandescence of calcium shields the hydrogen above it in some way; or (2) that the elevated "thunderhead" of calcium displaces the generally glowing hydrogen into an upper region where it is incapable of continuing to glow; or (3) that the rising of the calcium "thunderhead" displaces the hydrogen sideways, making it fall into the calcium valleys, where it glows.

The third view seems to introduce a mechanism which works in opposite ways for calcium and hydrogen: for it is the uprising calcium that glows in K_2, but it is the displaced hydrogen that glows in descending to a lower level.

The second view involves the idea of upheavals persisting for several days. The first view demands a special mechanism; it may be forthcoming, but it is unnecessary to develop it.

I incline to accept none of these three views, but rather to think that both the persistence of bright flocculi (in particular, calcium K_2 flocculi, involving the radiation of large amounts of energy for many days, or even months) and also the complementary nature of hydrogen and calcium flocculi may be more easily referred to the continued descent of matter from without upon the sun's surface. Hale's view of ascensional currents, unless I misunderstand it, leaves us in the position of having to supply energy to provide for radiation under conditions of dynamical loss during expansion. The descensional currents seem to afford a more hopeful aspect.

C. In the third place, let us consider the spectrum of a bright calcium flocculus in a disturbed region of the sun's surface—i. e., near a sun-spot. Probably in the great number of investigations which Hale is carrying out or has on his programme, one of the most interesting and important will be that which deals with the brightness of different parts of the spectrum in the wings of the K line—the photometric researches. It would appear that the bright K_2 line is nearly if not quite as bright as the continuous spectrum outside the dark wings of K_1. It would also appear that the narrow metallic absorption lines involved in the shaded edges of the broad K_1 line are not reversed bright. Now if the dark edges of the K_1 line are due to lower strata of calcium, then these strata must darken the photosphere and impair its power to make metallic lines due to vapor above them appear as absorption lines. The fact that the metallic lines remain absorption lines in the edges of K_1 affords means of arriving at an estimate of limiting values of the difference in effective temperatures of the strata in which the absorption of the broad edges of K_1, and the narrow metallic lines involved in them originates. It is evident that the same argument which would stand in the way of our assigning a lower level to the calcium vapor will stand also in the way of our inverting the layers. And thus until we have photometric observations to help us, we are, I think, driven to regard the seat of absorption for both the broad calcium line and the narrow metallic lines as residing in one and the same reversing layer. And we are left with the need to find explanation for the formation of both broad and narrow absorption lines in that one layer.

Hale's imagery in dealing with solar flocculi is of solar "thunderheads," analogous with the cumulus clouds connected with terrestrial thunderstorms. If in attempting to account for the persistent emission of radiant energy from such ascensional clouds of calcium we try to develop Schwarzschild's idea of radiative equilibrium, we are met by the difficulty that if a bright K_2 flocculus is incandescent calcium vapor floating over cooler calcium which gives a broad absorption line (K_1), then a great part of the photospheric radiation available for keeping the flocculus glowing is cut off by the cooler strata of calcium below; and unless we are willing to admit that the glowing of the flocculus is of the nature of fluorescence, we are driven back upon electrical or chemical modes of maintaining the radiation of the flocculus. A simple mechanism seems available, if we admit a combination of the recognized emission of corpuscles by an incandescent photosphere with gaseous or vaporous matter settling in upon the sun from without.

Hale has carefully set forth in his book the case for temperature variation as capable of being made the basis of explanation of sun-spot and stellar phenomena. My own conviction is that that case is only strong enough for a general exposition of the subject and for showing how the new methods give hope of our being able to substitute a better aspect. This is, of course, Hale's point of view. But no one can read his recent scientific papers without realizing that he is committing himself more and more deeply to that -doxy. (I naturally refrain from prefixing to that hyphen either ortho- or hetero-.)

In his experiments with the electric furnace, he is dealing with vapor permanently inclosed in an incandescent tube, which according to all the work of H. A. Wilson, Richardson, Horton, and others must be full of free corpuscles. The substitution of the furnace in place of the arc must give us most important advances of knowledge of the radiation of vapor in a considerable space under conditions specifiable in terms of temperature. But it must never be forgotten that the furnace is electrical both in name and nature.

Nothing can be less suitable for our purpose of studying temperature variation than methods based upon arc and spark. Each epitomizes a vast range of conditions both electrical and thermal. The one gives instantaneous explosions of the most complicated conditions; the other exhibits phenomena which depend on continued flux of vapor through exceedingly varied conditions, electrical and otherwise. Out of this agnostic *impasse* safety lies along the path of the method of experimenting adopted by Hale, but the goal is not yet in sight.

I may summarize the aspect which I venture to suggest, as follows:

We have suns with incandescent photospheres maintained by convection currents which carry the energy from within the sun to the radiating photosphere. Such suns by their gravitationally attracting power are constantly drawing matter in upon their surface. But their radiation exerts by the agency of light-pressure a selective action on matter so attracted. We may divide the attracted matter into three categories: (1) molar matter, in masses large enough to be drawn in spite of light-pressure, having diameters longer than about $2\frac{1}{2}$ times the wave-length of light, (2) molecular matter, in masses small enough to escape in virtue of diffractional effects the repulsion of light, having diameters less than about one-tenth of the wave-length of light, and (3) light-driven matter, in masses intermediate between molar matter and molecular matter, and subject to the repulsion of light.

The reversing layer is provided by molecular matter constantly streaming across what we may call a critical envelope concentric with the sun and probably is in a slightly modified state of radiative equilibrium. The constant flux of matter here involved is provided by those constituents of the planetary whirl of molecular matter circulating round the sun, which are directed inward upon the sun in virtue of properly directed collisions. This constant flux appears to me to be of the essence in the suggested aspect.

The molar matter may be active in producing local disturbances which result in sun-spots and prominences.

The light-driven matter is probably intimately connected with the apparent repulsion of comets' tails.

The corona is formed and maintained by the joint action of molecular matter and light-driven matter, the former probably being involved in the arches and the latter being responsible for most of the long-drawn streamers.

Under the influence of local disturbances, regions of the sun may emit corpuscles which succeed in penetrating the lower strata of the reversing layer and cause higher strata to glow as if their effective temperature were higher than lower strata, and thus bright flocculi arise.

The difference between stars of the first and second type might be referred partly to the difference in the relation between the critical envelope and the photosphere, as conditioned by the mass and density of the nucleus within the photosphere, and partly to the inability of solar stars to retain hydrogen and helium (Schuster, *Astrophysical Journal*, **17**, 197, 1903).

The peculiar features of stellar spectra of third and fourth types might be viewed as the result of the accidental nature of the molecular matter circulating round them. The third-type stars would require titanium meteorites, while those of fourth type would be fed by comets.

The most difficult part of the whole matter seems to lie in accounting for the organized rotation of the vapor which we observe in the spectroscopic determination of the solar rotation. The difficulty lies in the reconciliation of the high planetary velocities that must exist in the whirl of gas, with the low value of the observed velocity on the sun's equator. It would seem certain that the survival of narrow Fraunhofer lines must be a residual phenomenon.

If the sun's mass were to increase by 4×10^9 grams per second for a million years, the period of the earth in its orbit (the length of the year) would be diminished by $\frac{1}{1000}$ of a second. Such an increase of mass would be brought about by a continuous stream of matter over the whole surface of the sun at a rate of about 6.6×10^{-14} grams per second per square centimeter; that is, by 30 particles (each of diameter $\lambda/10$ and sp. gr. 5.5) per second per square centimeter, or by gas of molecular weight of air streaming in with velocity 1 cm/sec. at pressure $75\times 10^{-12}\times$atmospheric pressure, or by 3000×10^6 molecules of air per second per square centimeter.

No one can be more conscious than myself of the immaturity of this suggested aspect. I have tried in setting it forth to steer a course between the unintelligible by reason of brevity and the unendurable by reason of length, and the statement of the case needs must suffer. But it would seem well to submit it for what it is worth to the tender mercies of workers who may be ready to co-operate in developing the best sides of it and eliminating the bad.

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